ROBOTICS

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*This book is dedicated to Nickolas Vescio who touched
the hearts of all those he came in contact with.*

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PREFACE

In the last ten years we have seen technology develop at such an alarming rate that we are almost overpowered and frightened of what the future may hold. With the development of the silicon chip, we have seen the space required for a computer shrink from a room filled with equipment to a space smaller than a cigarette package with increased computing capacities. The development of the electronic chip has opened up what some experts have coined the *Second Industrial Revolution*. Many consider robots to be the primer on the revolution.

The use of robots is no longer a dream. The widespread use of robots in our society is increasing by geometric rates and will continue to increase in the future. With the increased use of robotic technology, the need for training in this area becomes more prevalent. The purpose of this text is to present material in a technical manner for training in the area of robotics, in addition to addressing what robots can do *for us* as well as *to us.*

The text is a comprehensive approach to teaching the technical aspects of industrial robotics. The book is divided into three sections: section one—chapters 1 through 4—deal with the general concept of robotics and its use in manufacturing. Section two—chapters 5 through 8—and section three—chapters 9 through 12—deal with a more in-depth study in electromechanical power systems and robot control systems respectively.

The book is written for vocational-technical schools and college and university programs. It would also make an excellent textbook for industrial training programs—as well as a reference book for those interested in robotics.

The authors would like to thank the many companies that provided photographs and technical information for preparing the manuscript. With their cooperation much of the up-to-date material was provided for the book. The authors also extend thanks to our wives for their patience and understanding during the manuscript preparation.

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ROBOTIC DEVELOPMENT

Forces behind Automation and Robotics

The United States is the most productive nation in the world. However, today the United States is seeing her domination being slowly eroded away by Japan and other Far Eastern countries. One has to wonder how this could happen to the strongest, most productive nation in the world. To answer that question all one has to do is review our performance the last 20 years.

Through the 1960s the United States enjoyed an annual growth rate of about 3 percent of productivity. But since 1966 the rate of productivity has declined from a positive growth of 3.2 percent yearly to a negative 1.7 percent in 1982. Figure 1–1 graphically shows the declining trend in productivity the United States is experiencing. However, today, several economists are predicting that manufacturers employing automated manufacturing systems coupled with the use of robotic technology can help to revitalize America's productivity.

Although the United States is losing ground in many areas of manufacturing, she can still boast of her superiority in agriculture. The average American farmer produces enough food to feed 109 people. This is about ten times higher than the Soviets. Even the Japanese must import one-fourth of their food and one-half of their grain needs.
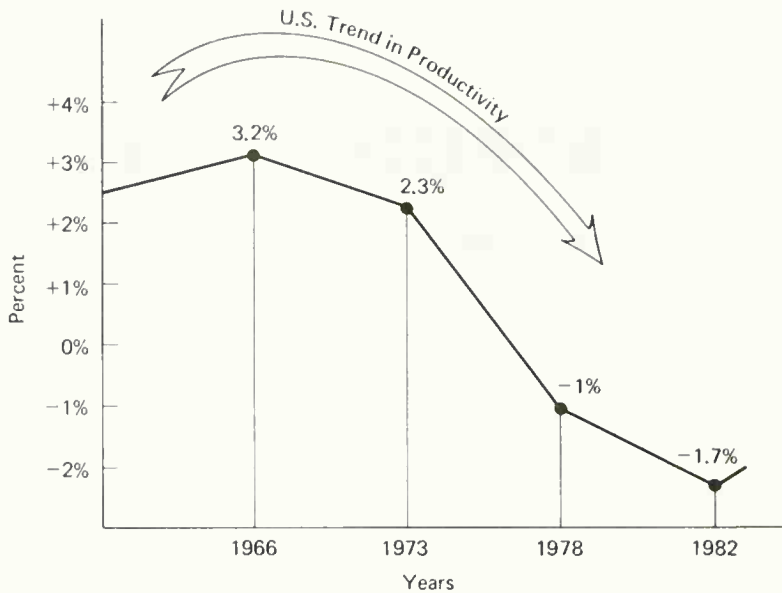
Figure 1–1.   U.S. rate of productivity.

How did the United States meet the growing demand for more agricultural products with a diminishing work force—A work force that was being lured away by the call from manufacturing? The United States was able to meet the challenge through *mechanization*, what most experts consider to be the forerunner of *automation*.

The U.S. agricultural industry is the most mechanized agricultural industry in the world. Only 3 percent of the U.S. labor force is engaged in agriculture. Yet the American farmers are able to produce enough food to feed the people of America as well as export surplus products to foreign countries.

Today the cry for greater productivity in other areas of the economy goes out. *Productivity* is the word that is foremost on the minds of most of us. Economists and government, business, and labor leaders generally agree that productivity is the key to restoring the American economy and maintaining our standard of living.

It is quite obvious that in order for the United States to be more productive and remain competitive, a change has to take place in our methods of manufacturing. Some experts say that change has to be the *incorporation of automation*. Most feel that automation can do for manufacturing what mechanization did for agriculture. It is evident that in order for the United States to be productive and remain competitive, some degree of automation will be required in every company.

It has been pointed out that mechanization is the forerunner of automation. However, there is a major difference between the two. This difference lies in the system and in machine control. Mechanization has been used to replace manual labor, whereas automation has enhanced mechanization by giving the system its intelligence. Even though manual labor, coupled with mass production and mechanization, has met the demand of yesterday's requirements, it cannot meet today's market requirements.

The demand for improved quality, shorter lead times, and reduced product cost are a few of the problems facing manufacturers. The recent recession has forced manufacturers to focus more attention on their methods of operations. Most experts agree that companies with the foresight to invest in new production equipment and develop better quality products will benefit by gains through increased productivity and better product reliability.

Why is the use of automation and robotics more attractive today than it was a decade ago? Some would suggest that the technology has been available for several years but implementation was not economically feasible. But with the rapid rise in labor cost, due mainly to inflation, and reduction in computer power cost, automation is quite feasible. Today a computer chip that costs about $6.00 is capable of replacing a computer that occupied a space the size of a room and cost over $1 million. With the reduction in computer cost, today's shift is toward automation.

The demand for reduction of inventories, lower product cost, improved quality, and increased productivity are the driving forces behind automation. Automated manufacturing systems, coupled with the use of robotic technology, are destined to change our methods of manufacturing. Many experts are predicting that the use of computers, automation, and robots will lead to a "second industrial revolution." Many consider that *robots* will play a major role in this technological development. No doubt companies that use robot technology effectively stand to reap benefits down the road.

There are those who foster the idea that the use of robots in the United States—approximately 7000 in use today—has idled or will idle part of America's work force. Arguments against this idea can be substantiated by the ever-increasing number of unemployed steel workers in the United States today. Failure to modernize has meant the demise of many steel companies. One should realize that it has not been the use of automation and robots that have idled many workers in the steel and automotive industries, but our inability to compete with countries who are using more modern manufacturing practices. Automation and robotics has enabled countries like Japan to produce more reliable low-cost products.

Figure 1–2.   General public's conception of a robot. (This was the robot used to greet people at the 1983 Robotics show in Chicago.)

The general public is somewhat knowledgeable about automation, and most agree that some form of automation is a must in order to be competitive. However, when one mentions the use of robots, a certain amount of anxiety and unrest is generated. Part of the problem is that most of the general public does not have the foggiest notion of what a robot is (see Figure 1–2). Thanks to science fiction writers and the motion picture industry, the misconception of robots has been well grounded in the public mind and kept alive since its origin in the early 1920s. The next section discusses how the misconceptions came about.

What Constitutes a Robot?

Robots have long played important roles in the movies and on television. Movies such as *Star Wars* and *Return of the Jedi* presented robots in a favorable light with the two comic robots R2D2 and C3PO. However, most literary works of the past have shown robots in a more unfavorable light. The robot many times has appeared as a threat to mankind rather than a help. To really understand why many people regard the robot as a threat, one has to go back to the robot's origin.

The word *robot* comes from the Czech word *robotit*, which means "to drudge" or "to do menial, unpleasant work." The word was coined in a play by the Czech dramatist Karl Capek in the early 1920s. The play was entitled *R.U.R.* (Rossum's Universal Robots).

So that the reader can better understand how the misconception of the robot became so embedded in our minds, it would be well to briefly review Capek's play. With the help of his son, Rossum developed the formula for making mechanical workers, known as robots, whose only function was work. The inventors rejected every ingredient in the formula that did not directly contribute to the progress of work. Their concocted mechanical men and women were more perfect than humans in many ways. They were extremely strong and dedicated to the task of work. Some were even quite intelligent. About the only thing the robots lacked was the presence of a soul or emotional awareness.

At the onset of the play a young, attractive lady sets out to rectify the inhumane treatment the robots were receiving. She confronted the robot factory's manager concerning the situation. Just as most playwriters use romance to enhance a story, Capek interjected romance in his play as well. At their first meeting the young manager wooed the young lady and captured her hand in marriage.

Over the next ten years the factory flooded the world with robots. However, during this time the young lady was able to fulfill her original ambitions to liberate the robots. She persuaded the plant physiologist to secretly change the formula—a change that provided some robots with other interests besides work.

As some might expect, the robots that possessed the human traits were able to organize the lesser robots and turn them against mankind. The robots eventually annihilated all of mankind except for one human being. After the annihilation of mankind the robots were faced with a tremendous problem. Their parts were wearing out and needed replacing. The robots made one great error. They saved the wrong individual. The man they spared, the company's builder, could not duplicate the lost formula. But as fate would have it, two humanized robots of different sexes appeared on the scene and mankind was saved from extinction.

Capek's play poses some theories that are still being considered today. Robots are more productive than humans. They can perform work more cheaply and are certain to take jobs away from mankind. In a sense this is true. But robots are relieving men and women from boring and unpleasant jobs.

It is evident that Capek had some apprehension concerning the effect of machines on the working man. No doubt he felt that man was being dehumanized and that man would eventually lose the individuality that centered around his work. The misconceptions spawned by

the play are still alive today. And even today robots are receiving some unjust criticism. A lot of this is due to the lack of knowledge concerning the subject of robots. Before one is critical of what robots can do to us, one must first understand what a robot is.

There are several definitions floating around concerning robots. Some experts define them as *blind, stupid, one-arm machines* capable of performing simple tasks. However, the most accepted definition has been published by the Robot Institute of America:[1]

> A programmable, multifunction manipulator designed to move materials, parts, tools, or special devices through programmed motions for the performance of a variety of tasks.

There are certain points that stand out in this definition. The robot is a machine. It can be programmed and reprogrammed to do several tasks. And because of its inherited programming capability, one can expect to find the robot functioning in many different jobs. These jobs will be located in manufacturing as well as other aspects of society.

Dan Whitney of Draper Laboratory best summarized the definition of a robot in layman's terms in a recent interview. Whitney defined a robot as a machine. It is very obvious that when one views robots as machines our expectations may be different. It is apparent that machines are designed to perform certain functions, and we should not expect anything else.

Some people feel that robots are the answer to society's problems. Although this is not true, robots can boost productivity, not because they are faster than humans but because they work at a steady pace. Thus, they outperform many workers, especially those doing repetitive, boring jobs. But most of all one must remember that robots are here to provide a service rather than to threaten mankind.

Historical Development of the Industrial Robot

For several years robots have been a fascinating subject for writers. Today robots are finding their place in all walks of society. They are being used from industrial applications to the far outreaches of space. Today the robots are even performing useful services in the area of law enforcement. Law enforcement agencies have utilized the robot to dismantle bombs as well as to hold suspects at arms. These accomplishments are quite impressive considering the technology is only approximately 25 years old. However, today's acceptance of the robot did not come easily. The inventor and the developer spent several agonizing

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[1] From *A Glossary of Terms for Robotics*, National Bureau of Standards NBSIR 81-2340.

nights during its early development. Recent interviews with George DeVol and Joe Engelberger bear this out. George DeVol, a well-known inventor, holds the patent for the first industrial robot. Joe Engelberger, founder and president of Unimation, is considered the father of the industrial robot.

DeVol patented his concepts of the industrial robot in 1954. He presently holds several patents related to the industrial robot. In addition to his patents on the industrial robot, he holds patents on such devices as photoelectric controls, magnetic recording systems, and the first teachable machine.

After DeVol patented his robot idea, he faced an insurmountable problem—financing his invention. Without success he attempted to sell his idea to some of the leading corporations in the United States. Some of those companies who rejected DeVol's idea are in the robot business today.

In the mid-fifties DeVol met a young engineer by the name of Joe Engelberger at a party. Engelberger was employed by Aircraft Products, a division of Manning, Maxwell, and Moore. Engelberger was impressed with DeVol's idea. He persuaded Aircraft Products to become involved in the development of the industrial robot. But it was not until Aircraft Products was acquired by Consolidated Diesel Electric that the much-needed capital was made available. From this early venture *Unimate* was born in 1958.

In 1961 the first robot developed by Unimation, known as Unimate, was sold to General Motors. It was used in a die casting operation. The word *Unimate* stands for "Universal Automation." The Unimate, like many other robots used early in industry, carried a name other than a robot. As of July 1982 Unimation had sold over 7500 robots.

Unimation has held the number one position in the sale of industrial robots. However, Unimation was acquired by Westinghouse Electric for a reported $107 million in January 1983.

At about the same time as Unimation was being formed, a company known as Versatran, a division of A.M.F., became interested in the robot. This interest was generated through its work with manipulators used on atomic energy projects. Versatran was formed in 1958. In 1979 Versatran was purchased by Prab Conveyor.

Prab, another leading robot manufacturer, began in 1961. The company was known as Prab Conveyor until the name was changed to *Prab Robots Incorporated* in 1981. Prab developed the Prab line of industrial robots in the late 1960s. The first machine was sold in 1969. They since have installed over 2000 robots throughout the world. Prab's industrial robots account for about 50 percent of their total sales.

Some other major robot manufacturers involved in the early development of robots for commercial use were DeVilbiss, Asea, and Cincinnati Milacron. The first DeVilbiss robot system was installed in 1971.

DeVilbiss is one of the leading producers of finishing robots. In 1982 DeVilbiss announced a new arc-welding robot. Asea was one of the early developers of the anthropomorphic robot unit. *Anthropomorphic* means "humanlike in form." Asea's first anthropomorphic all-electric unit was installed in 1973. Cincinnati Milacron entered the robot market in 1976. The Cincinnati Unit was a hydraulic anthropomorphic unit. Cincinnati ranks second in the sale of robots. Cincinnati's robot sales account for about 10 percent of their total business.

During the late seventies and early eighties a big push in robotics has been in the area of assembly. In 1978 the *Puma Robot* was developed by Unimation for General Motors. Also in 1978 the *SCARA Robot*, a university-born assembly robot, was developed. The robot was developed in the laboratory of Professor Makino, Precision Engineering Department, Yamanashi University, Japan. To help support the research efforts, a consortium called "SCARA Research Group" was formed. SCARA stands for "Selective Compliance Assembly Robot Arm." The group started with 5 companies in April 1978 and finished with 13 companies in March of 1981. After the consortium was dissolved, several of the companies in the group chose to sell their own versions of the robot. Of those companies marketing versions of the SCARA Robot, the *Sankyo Seiki* is probably one of the better robots for assembly.

Several manufacturers entered the robot market in 1982. Companies such as IBM, Westinghouse, General Electric, Bendix, and Hobart publicly demonstrated many of their models for the first time. Although this was the first official announcement for most of these companies, many had been building robots for in-house use for several years. IBM began experimenting with robots in 1972; General Electric and Westinghouse installations date back to the mid-seventies.

Presently there are over 50 robot manufacturers in the United States and approximately 300 worldwide. With the entrance of several large corporations in the market, the distribution of sales is certain to change. The entrance of the additional large corporations may be the shot in the arm the robot industry has needed. For several years many U.S. manufacturers have regarded robots as a novelty. On the other hand Japan accepted the robot with open arms.

Evidence of Japan's early acceptance of the robot can be seen by the rapid growth of robotics technology in that country. Japan's first industrial robot was developed in 1969. This was two years after the first Versatran Robot was imported to that country. Japan's enthusiasm is also evident in that the Japan Industrial Robot Association (JIRA) was founded in 1971, four years before the Robot Institute of America (RIA) and six years before the British Robot Association (BRA). So one can say that Japan did not agonize over robotics as other countries have. They took the American idea and developed that idea to its fullest potential. Today Japan is the world's largest user of industrial robots.

REVIEW QUESTIONS

1. Since the turn of the century the United States has changed from a predominantly agricultural society to an industrial society and is now a service-oriented society. Approximately what percent of the labor force is engaged in agriculture? How has the agricultural industry been able to meet the agricultural needs with such a small labor force?

2. The United States is still the most productive nation in the world. What foreign country is considered our greatest competitor?

3. What word concerning manufacturing appears to be foremost on the minds of people in the United States today?

4. *Mechanization* can be considered a forerunner of *automation*. Explain each term and cite the difference.

5. The GNP (gross national product) rate was a negative number in 1982. What are some factors you feel contributed to this decline in productivity?

6. What are the driving forces behind automation and robotics?

7. Why is automation becoming more attractive to manufacturers today?

8. Robots are considered to be a key element in automated manufacturing. Give the definition for a robot and point out the key factors in the definition.

9. What appears to be the general public's concept of a robot?

10. Who was the Czech playwright who coined the word *robot*? Why did he write the play? What does the Czech word *robotit* mean?

11. Who were George DeVol and Joe Engelberger?

12. In what year was the industrial robot patented?

13. What was the name of the first company to produce a robot and in what year was the first unit sold?

14. Some people believe that the use of automation and robots will replace human workers. Others believe if automation and robots are not incorporated into manufacturing we will lose a far greater number of jobs. What statements can you give in defense of both views?

15. Summarize the historical development of the robot.

16. What country is the greatest user of robots today?

BASIC CHARACTERISTICS AND FUNDAMENTALS

Major Components

The industrial robot bears very little resemblance to robots represented in science fiction. Since the robot was developed to perform tasks normally performed by humans, it is natural for the robot's features to be compared to those of a human.

The jointed-arm robot, the most common robot configuration, is often referred to as *anthropomorphic* or *humanlike in form*. Although this type of industrial robot is regarded as humanlike in form, it mostly resembles a single arm attached to a stationary base. Figure 2–1 illustrates the common parts of the jointed-arm robot. In comparison with the human body, the robot possesses such features as a hand, wrist, arm, elbow, shoulder, and waist. This arrangement can best be described as an inverted arm. The inverted arm does have a distinct advantage over an arm arranged in the upright position. It enables the robot to pick up material or components located at its base. Anthropomorphic robots will be discussed later under motion configuration.

The robot consists of three major components: the mechanical unit, known as the *manipulator*; the brain, known as the *controller*; and the *power supply*. Figure 2–2 shows the relationship among these components.
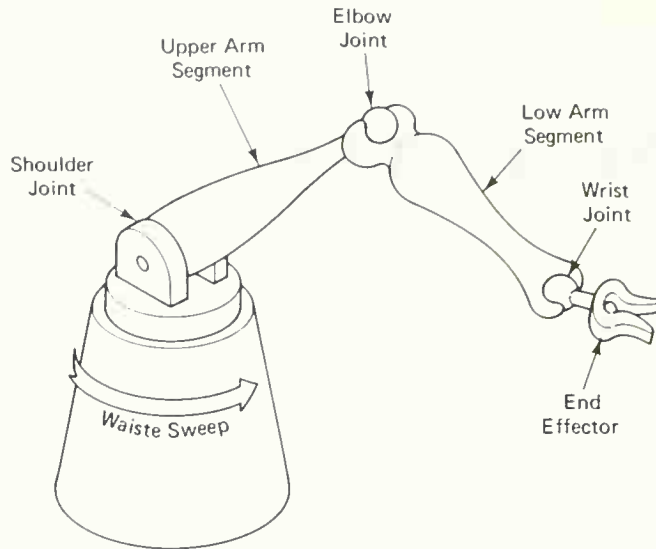
Figure 2–1. Joint and segment arrangement of a jointed-arm robot.
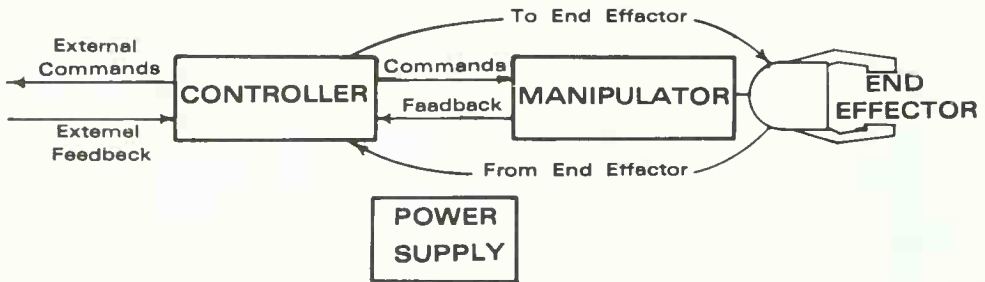
Figure 2–2. Relationships of robot components.

It is not surprising that one of the components would be called the manipulator since that was a common name given robots during their infancy. The early robots were often called *universal transfer machines* or *programmable manipulators* due to the stigma attached to the word *robot*. As was pointed out, the manipulator is the mechanical unit. It is the component that does the work and gives the robot its dexterity. Of course, the amount of dexterity depends on the number of joints or degrees of freedom the robot employs. The different degrees of freedom will be discussed later in the text.

The manipulator's main responsibility is performing the manipulative function of positioning the robot's hand. The robot's hand is tech-
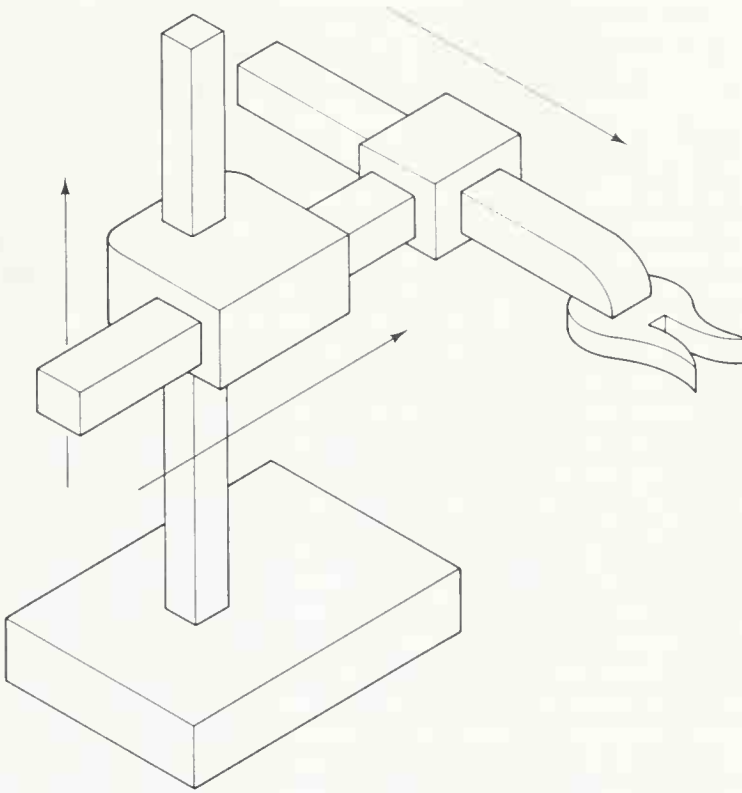
Figure 2–3. Sliding-segment arrangement.

nically known as the *end effector*. In order to provide the manipulator with a certain amount of dexterity, several mechanical linkages and joints are employed. These series of segments may be jointed or may slide relative to one another. Figure 2–1 shows the joint and segment arrangements of the jointed-arm robot. Figure 2–3 illustrates the sliding segment arrangement.

The mechanical unit, or manipulator, has often been labeled the skeleton, muscles, and nerves of the robot. Movement of the various joints and segments of the manipulator are accomplished by actuators. The actuator is a motor or transducer that converts electrical, hydraulic, or pneumatic energy into another form of energy that causes the robot to move. The actuators can be mounted directly at each joint or they can drive the robot indirectly through the use of gears, cables, chains, or ball lead screws.

Other components used in conjunction with the manipulator may vary according to type of power supply employed and levels of so-

phistication. If the robot is a closed-loop system, internal sensors may be used to communicate to the controller. Feedback sensors such as encoders or resolvers may be used in communicating the various segments or joint location positions.

Some robots may employ more than one type of sensor. This is especially true if one is interested in controlling velocity as well as positioning. Different types of sensors will be discussed later.

The less sophisticated robot, the open-loop system, may use a simple limit switch. The switch is activated when the robot's arm has reached its destination.

In addition to sensors, various control valves are employed on the manipulator. Hydraulic and pneumatic control valves are used to regulate and control the flow of air or oil to the various actuators. In summary, the manipulator not only includes the various segments and joints but also the various actuators, sensors, switches, and control valves.

One of the key factors leading to the increased use of robots in industry has been the improvements made in the robot controller. With the development of the silicon chip the controller is more powerful and considerably cheaper today. Programmable controllers, microprocessors, and minicomputers that were a luxury a few years ago are now available on many robots at a reasonable cost.

The controllers on today's robot can vary in complexity and capability. The cheaper, less-sophisticated robot, the pick-and-place variety, may use a rotary drum. Programming of the drum is controlled by the setting of cams and switches. The setting of mechanical stops on the various axes is used to position the robot's hand. Under this arrangement normally only two positions per axis can be achieved.

For the more sophisticated or intelligent robots the microprocessor or minicomputer is used. The minicomputer has greater memory power for storing positions and sequence data. This increased storage of points provides a smoother movement of the manipulator. Also, the increased computer power enables the robot to interact with its environment.

In summary, the controller serves three functions. First, the controller functions as memory by storing the necessary positioning and sequence data. Second, the controller controls the movement of the manipulator. It initiates and terminates various moves. Third, the controller communicates with the peripheral equipment. It can be used to turn on adjacent equipment or can perform a waiting function until adjacent equipment cycles. In the more sophisticated arrangement where external sensors are used, the controller can be programmed to recognize certain conditions and make the necessary adjustments or branching routines.

Although we live in the age of computers, one must remember that other control devices are available. The main thing to remember is

to purchase a robot that is capable of doing the job. Avoid specifying a robot that is an overkill. Other factors, such as speed of operation, accuracy, repeatability, and ease of programming, must also be considered when selecting the proper control device.

The power supply provides the energy to drive the actuator. The three basic power supplies are *electrical*, *hydraulic*, and *pneumatic*. The selection of the type of power supply is generally determined by the application. If the application is a lightweight pick-and-place operation that requires speed and accuracy, then a pneumatic source may be preferred. If the application is in an explosive area, a pneumatic or hydraulic source is a must. For those operations that require the handling of heavy objects, the hydraulic unit is recommended. Hydraulic units are considered faster than electrical units. The hydraulic unit can achieve good accuracy and repeatability when used with accurate feedback sensors.

Although the hydraulic unit is generally used for handling heavy objects, there are hydraulically powered robots recommended for light applications. The IBM 7565 robot is a good example. The IBM 7565 robot has proven itself in the area of assembly parts with very close tolerances.

The use of electrical power supplies is increasing, especially since greater emphasis is being placed on automated assembly. The electrical unit is not as strong or fast as the hydraulic unit but it does require less floor space. Another advantage is that the electrical unit can be used in a clean-air environment. The electrical unit also makes far less noise than the hydraulic units.

Although there are three distinct types of power supplies, some robot manufacturers may use a combination of power sources. Some robots may employ an air over oil source, while others may be a combination of all three power sources.

To understand the working relationships of the various components of the robot we shall apply the block diagram in Figure 2–4 to an actual application. In the application the manipulator's end effector has been replaced with a spot welding gun. In order to assure proper fit and alignment of parts being welded, some type of outside fixture has to be employed. Loading of fixturing could be done automatically or manually. For the purpose of this explanation an operator will be utilized.

At the start of the cycle the operator loads the fixture, clamping the part in place. After the part is clamped, a signal is sent to the robot controller through an external feedback port. Upon receipt of the command the controller sends a signal to the manipulator to move the welding gun to the first preprogrammed point in the welding cycle. Upon arriving at the point, the controller sends a signal to the welding gun to initiate the weld. At the completion of the weld a signal is sent back to the control. The signal tells the controller the weld has been com-
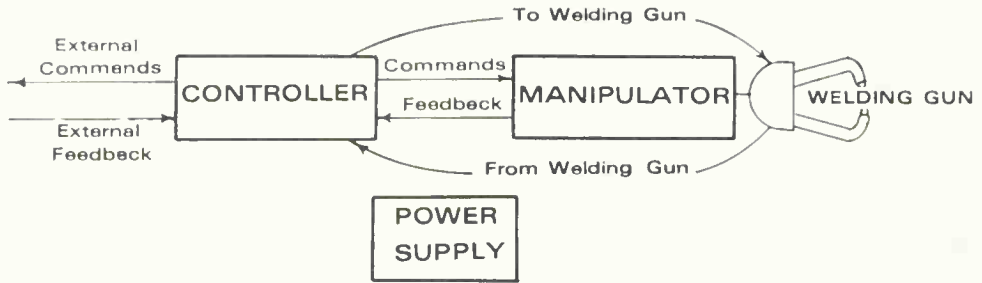
Figure 2–4.   Block diagram of welding application.

pleted. The memory of the robot addresses the next welding location, and the process is repeated until all of the welds are completed. When the last weld is completed, a signal is sent through an external command port to the clamping fixture to release the part. The part is unloaded, and a new part is placed in the fixture. The memory of the robot is reset for welding the next part.

Classifications of Robots

From some of the material presented one can see that robots vary in size, shape, and complexity of operation. The classifications of robots can be just as varied depending on whose classification you are using. In Japan there are basically six distinct classifications of robots. Although there are only two major classifications in the United States, some experts group robots into three classes: nonintelligent, intelligent, and highly intelligent robots. In order for the reader to understand the various classifications of robots, they need to be explored in more detail. Before discussing the different U.S. classifications, the Japanese classifications will be discussed. Not only is Japan the largest user of robots but Japan has a significant number of different classifications. In order to provide some insight into Japan's robot classifications, let's examine the Japanese Industrial Standards[1] definition for manipulators and robots.

[1] Japanese Industrial Standard JIS B 134-1979.

Japanese Definitions and Classifications

A *manipulator* is a device for handling objects as desired without touching with the hands and it has more than two of the motion capabilities such as revolution, out-in, up-down, right-left traveling, swinging or bending, so that it can spatially transport an object by holding, adhering to, and so on.

A *robot* is defined as a mechanical system which has flexible motion functions of living organisms or combines such motion functions with intelligent functions, and which acts in response to the human's will. In this context, intelligent functions mean the ability to perform at least one of the following: judgment, recognition adaptation or learning.

The various groups of Japanese robots are classified according to input information and teaching methods. Later in the text the Japanese and U.S. classifications will be compared.

The lowest Japanese classification is the *manual manipulator*. In this classification the robot is directly operated by a man or woman. The inherited strength of the robot is transferred to the operator, thus increasing the operator's reach and lifting capabilities. See Figure 2–5 for an example of this type of robot.

The *fixed-sequence robot* can be defined as a robot in which the predetermined sequences cannot be easily altered. A good example of this is the Pick-O-Matic fixed-sequence robot in Figure 2–6.
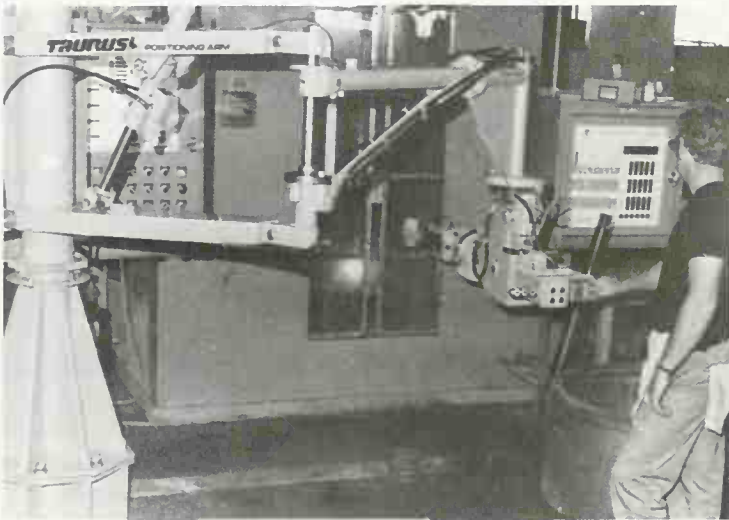

Figure 2–5.   Taurus manual positioning arm used to load axle shafts at a John Deere plant. (*Courtesy of Positech Corp.*)
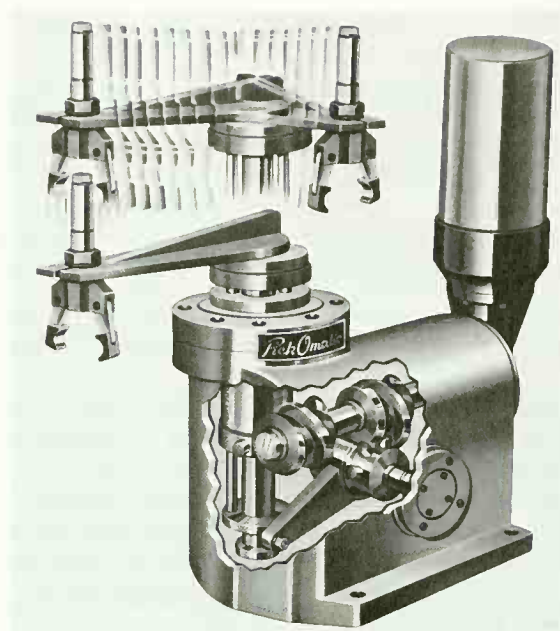
Figure 2–6. Pick-O-Matic model 2700 B fixed-sequence robot. (*Courtesy of PickOmatic Systems.*)

The next Japanese classification, which provides some programming flexibility, is the *variable-sequence robot*. The pick-and-place robots would fit into this category. They are the simplest version of the U.S. robots. As the name implies, they are well suited for picking up parts at one location and placing them at another location. The Seiko Model 700 (Figure 2–7) is a good example of this classification.

The *playback robot* has the distinction of duplicating the movement of the operator. A skilled operator, such as a painter, moves the manipulator's arm through a set routine in order to program the robot. While the operator is putting the robot through its task, the movements are recorded on magnetic tape or flexible disc. The robot will duplicate the operator's movements when placed in the playback mode. In Figure 2–8 an operator is programming a Thermwood robot to palletize boxes.

The *numerically controlled robot*, or computerized robot, is a model controlled by a computer. Programming is accomplished by transmitting instructions electronically. A computer terminal is used to input the data. Many servo robots employ this type of programming.

The *intelligent robot*, the most sophisticated robot, employs external sensing mechanisms in addition to internal joint sensors. The external sensors provide the robot with a certain degree of decision-making capabilities. The robot is able to interact with its environment and take
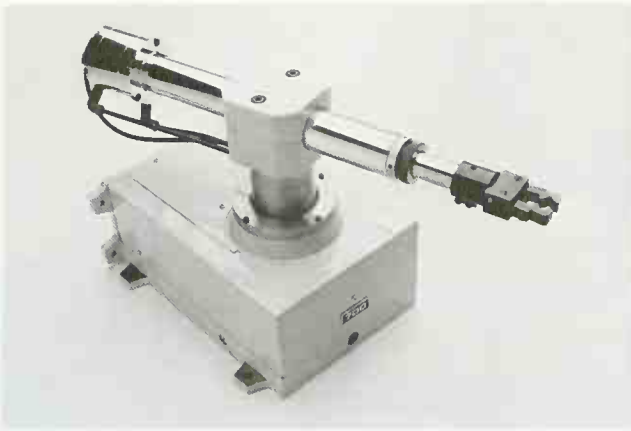
Figure 2–7. Seiko's model 700 variable-sequence robot. (*Courtesy of Seiko Instruments.*)

Figure 2–8. Programming of Thermwood robot to palletize boxes. (Photo taken at Robot 7 show in Chicago.)

corrective measures. Vision or touch sensors are generally used to provide the robot with the artificial intelligence. The IBM 7565 robot with its tactile and LED sensing falls in this classification (see Figure 2–9).
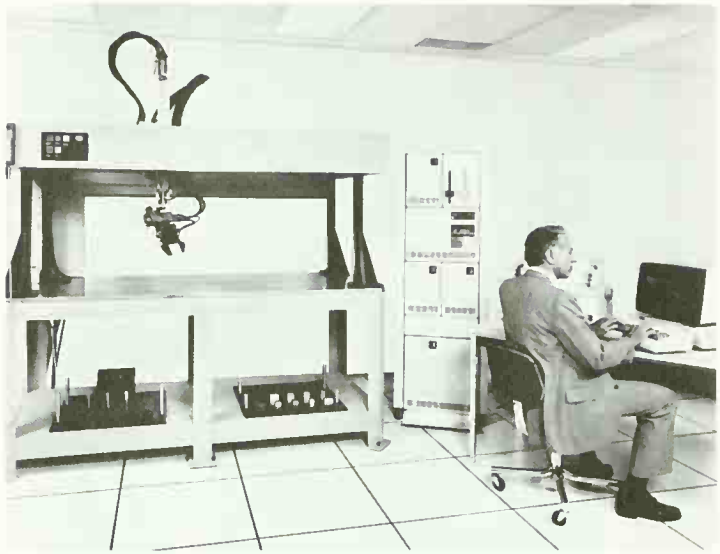
Figure 2–9.   IBM's 7565 advanced robotic system. (*Courtesy of International Business Machines Corp.*)

U.S. Classifications

For all practical purposes the U.S. classifications of robots can be grouped in two major categories: *nonservo* and *servo*. Although some experts contend there are three major categories, they regard the non-servo robot as a *nonintelligent* robot, whereas the servo robots can be classified either as *intelligent* or *highly intelligent* robots. The difference between the intelligent and highly intelligent robot will be discussed later. But consideration will first be given the two major categories, the nonservo and the servo robots.

The nonservo robot is an *open-loop system*. That is, no feedback mechanism is used to compare programmed positions to actual joint locations. In order to better understand this, a rather simple example, a modern washing machine, will be used. Although the washing machine is not a robot, it is a good analogy of an open-loop system.

At the beginning of the operation, the dirty clothes and the necessary detergents are placed in the tub of the washing machine. The timer is set for the proper cleaning cycle, and the machine is activated by the start button. The machine fills with water and begins to go through the various phases of the cycle such as washing, rinsing, and spinning. The machine finally stops after it goes through the set sequence of the timer. The washing machine is considered an open-loop

system because the clothes are never examined during the cleaning cycle to see if they are clean. Also the length of the washing cycle is not automatically adjusted to compensate for the amount of dirt in the clothes. The sequence and length of time are determined by the fixed sequence of the timer. No means of feedback is provided.

Nonservo robots are the simplest form of robots according to the U.S. definition. They are often referred to as "limited-sequence," "pick-and-place," or "fixed-stops robots." To help you better understand the operation principles of the nonservo, study the diagram in Figure 2–10.

The diagram is used to represent a three-axis pneumatic robot. For the sake of clarity only one axis is emphasized. At the beginning of the cycle the controller begins to move through the various steps or sequences. At the first step the controller sends a signal to the control valve of the manipulator. As the control valve opens, air is allowed to pass to the actuator or cylinder, causing the rod of the cylinder to move. As long as the valve remains open, this segment of the manipulator will continue to move until it is restrained by the end stops on the rod of the cylinder. After the rod of the cylinder reaches its length of travel, a limit switch is activated, telling the controller to close the control valve. The controller sends a signal to the control valve, which closes it. The controller then moves to the next step in the program and initiates the necessary signals. These signals may be to certain control valves or to the end effector (robot's hand). If the signal is to the end effector, it might cause the gripper to close in order to grasp an object. The process is repeated until all the steps in the program have been completed.

The servo robot, the more sophisticated robot, is a *closed-loop robot.* That is, the signal of the controller to the signal amplifier is dependent on the output of the system. In a sense a servomechanism is a type of control system that detects and corrects for errors.

The principle of servo control can be compared to many tasks performed by human beings. People use the principle of servomechanism
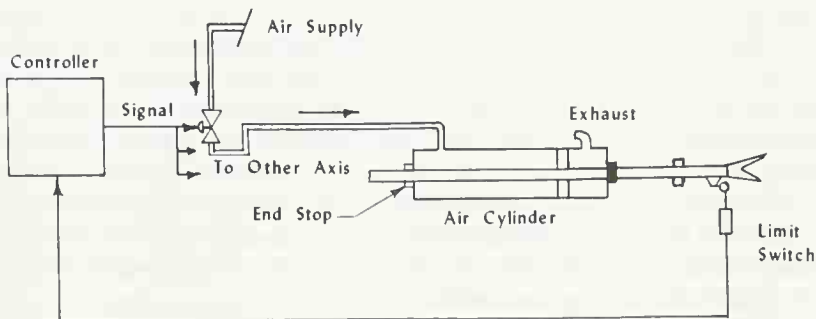

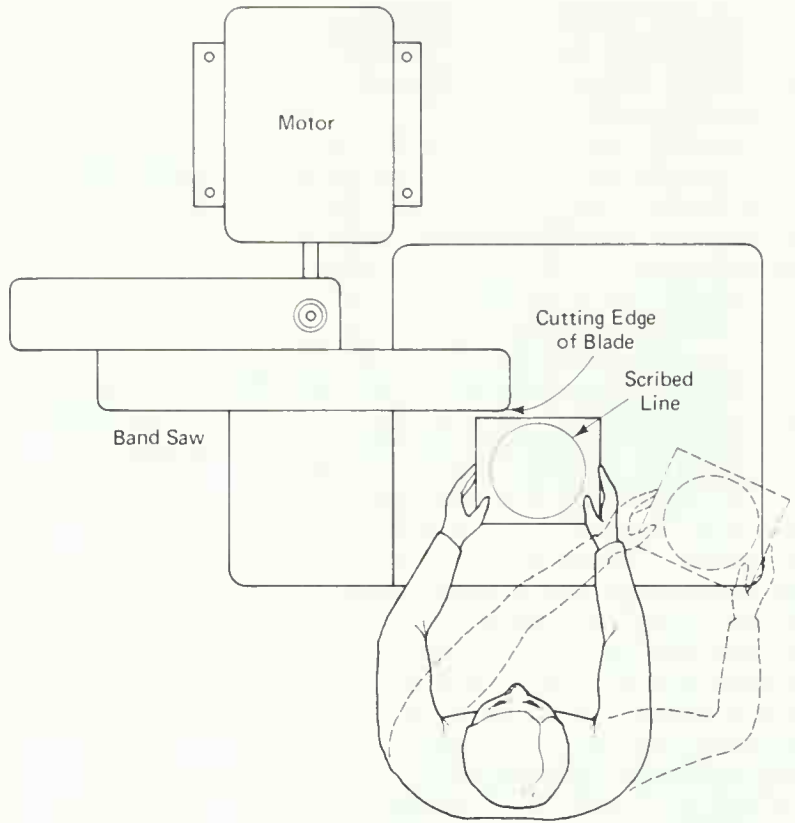**Figure 2–10.**   Nonservo diagram.

Figure 2–11. Human employing the principle of the servo mechanism.

in everyday living, from the task of operating an automobile to other manipulative tasks. To better understand the principle of servomechanism, a simple task of cutting a circle on a power bandsaw will be used, as illustrated in Figure 2–11.

The machine operator compares the actual position of the part to be cut with the cutting edge of the blade. The eye transmits a signal to the brain. The brain compares the desired position of the stock to the actual position of the stock. The brain then sends a signal to the arms to move the stock to the cutting edge of the blade. The eye is used as a feedback device, while the brain compares desired locations with actual locations. The brain sends signals to the arm to make the necessary adjustments. This process is repeated as the operator follows the scribed line during the sawing operation.

The diagram in Figure 2–12 is used to help explain the operating principle of the servo robot. The diagram is a simplified version of a six-
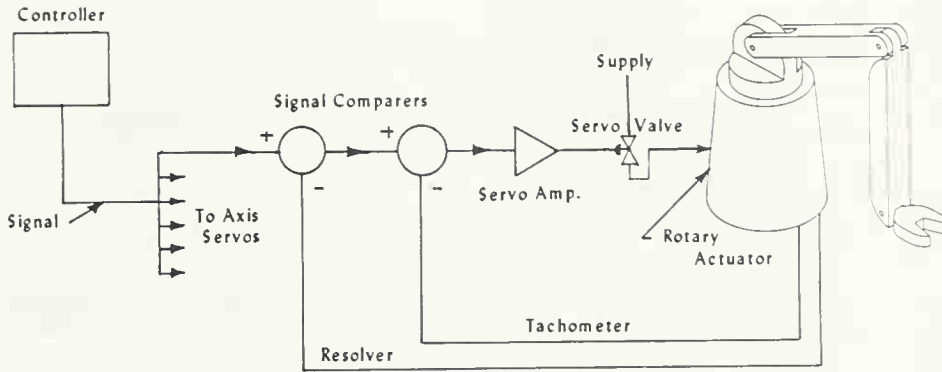
Figure 2–12. Servo diagram.

axis hydraulic power supply robot. Only one axis of the robot is shown in detail.

When the start of the cycle is initiated, the controller addresses the first desired location and interprets the actual locations of the various axes. The desired location signal generated by the controller is compared with the feedback signals from the resolver measuring units on the various axes of the manipulator. The difference in the signals, known as *error signals*, are amplified and applied to the servo control valves. The valves opens proportionally to the level of the command signals generated by the amplifiers. The opened valves admits fluid to the actuators on the manipulator. The actuators move the various members of the manipulator. New signals are generated as the manipulator moves. When the error signals reach *zero*, the servo control valves close, shutting off the flow of oil. The manipulator comes to rest at the desired location position. The controller addresses the next point in memory. It may be another desired position location or a signal could be generated to operate some peripheral equipment. The process is repeated until all steps of the program are completed. The tachometer measuring units are used in conjunction with the controller to control acceleration and deceleration of the movements.

The servo robot has a more sophisticated controller than the non-servo. The controller has the capability of executing several hundred steps. The controller may use point-to-point (PTP) or continuous-path (CP) motions. Some controllers have both PTP and CP capabilities. The different types of motion control will be discussed later in the text.

As previously mentioned, the servo classification can be divided into two distinct groups, *intelligent* and *highly intelligent* robots. The main difference between the two servo classifications is that highly intelligent servo robots utilize external sensors in addition to the regular joint in-

Table 2–1

COMPARISON OF ROBOTS BY DEFINITION

Item No.	Japanese Definition	U.S. Definition	
		Nonsophisticated	*Sophisticated*
1	Manual Manipulator		
2	Fixed Sequence		
3	Variable Sequence	Nonservo	
4	Playback		Servo—Intelligent
5	Numerically Controlled		Servo—Intelligent
6	Intelligent		Servo—Highly Intelligent

ternal sensors. The two most common types of sensors are vision and tactile. These sensors can provide the robot with certain decision-making capabilities. They help the robot determine its own actions and take corrective measures.

Table 2–1 is used to compare the U.S. and Japanese classifications. According to U.S. definitions, items 3–6 are considered to be robots while items 1 and 2 are not. Item 3 is classified as an open-loop (non-servo) robot, whereas items 4–6 are closed-loop (servo) robots.

The first part of this chapter has been devoted to the various robot components, classifications, and levels of sophistication. The remainder of the chapter will address the basic fundamentals of motion configuration, degrees of freedom, and work envelope.

Geometric Motion Configurations

Robots are available in various shapes and sizes. Although robots vary widely in shape, they are generally grouped in one of four major robot configurations. Some robots may employ more than one configuration. The different configurations are derived from the joint arrangement or the different geometric configurations the robot's work envelope approximates. The *jointed-arm* or *jointed spherical* robot configuration is the most common. The robot is often referred to as anthropomorphic or humanlike in form because it closely resembles the movements of the human body. The robot consists of various rigid segments, joints, and a base. The rigid segments resemble the human forearm and upper arm. The various joints, except for the sweep, depict the action of the wrist, elbow, and shoulder. The sweep represents the waist. Figure 2–13 shows the various segments and joints of Cincinnati Milacron's T³ robot.

The jointed-arm robot, also known as a *revolute coordinate* arrangement, performs work in an irregular work space. The work space gen-
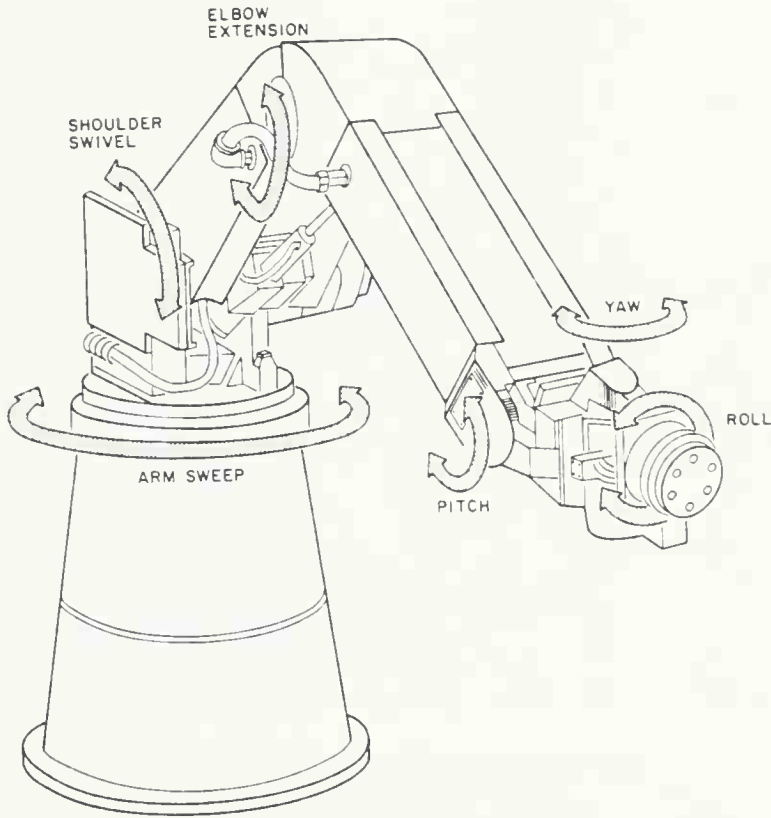
Figure 2–13.   Cincinnati Milacron T³ robot. (*Courtesy of Cincinnati Milacron.*)

erally refers to the region the robot is capable of reaching. The reach is determined by some designated point on the robot's wrist. The jointed-arm robot does provide a reach that is more flexible than many of the other types of configurations. However, different points of locations in the work space can have a definite effect on accuracy, repeatability, load-carrying capacity, and dynamics. Figure 2–14 shows the irregular work envelope of a typical jointed-arm robot.

The *cartesian coordinate* robot consists of three intersecting perpendicular straight lines. The origin is the intersection. The cartesian coordinate system is often referred to as the *XYZ* system (see Figure 2–15). By having all three axes start and stop simultaneously, a smoother motion of the tool tip can be achieved. This allows the robot to move directly to its designated point instead of following a trajectory parallel to each axis. Figure 2–16 will help illustrate this point. The cartesian coordinate robots have certain advantages over some of the other coordinate systems. One worth noting is that the accuracy, repeatability,
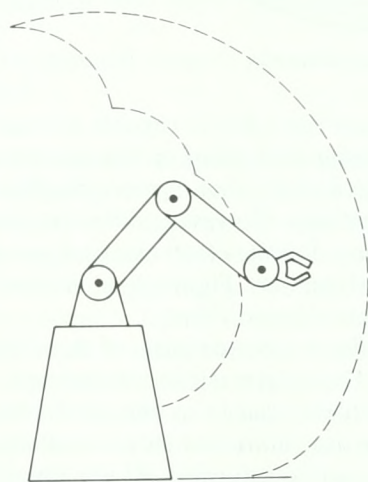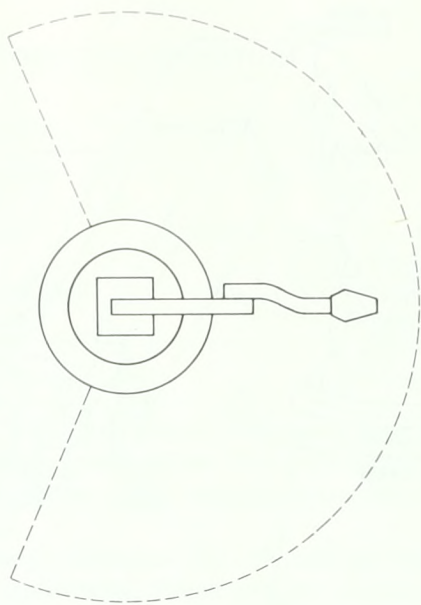
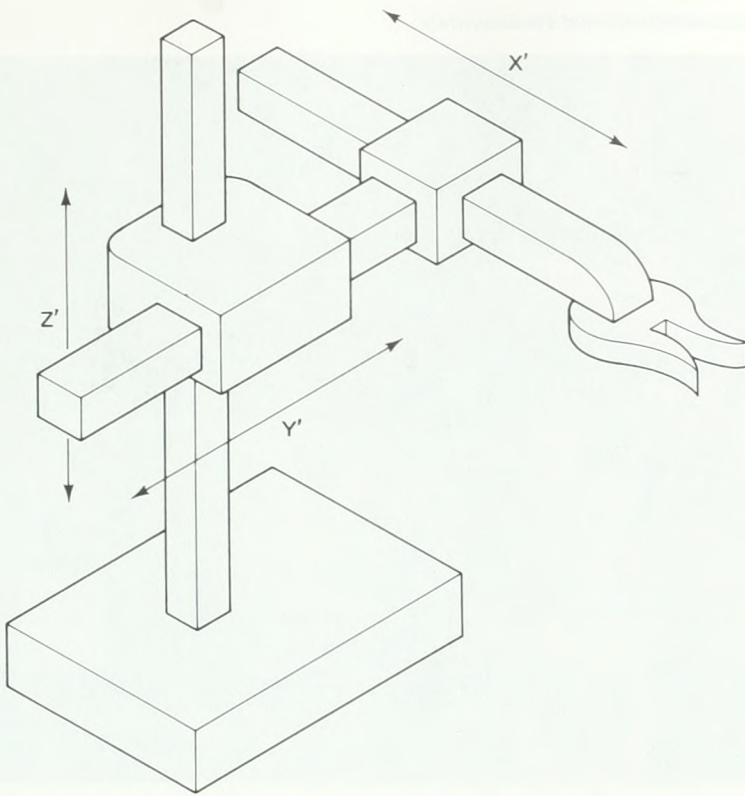**Figure 2–14.** Reaching flexibility of the jointed-arm robot.

Figure 2–15. Cartesian coordinate robot.

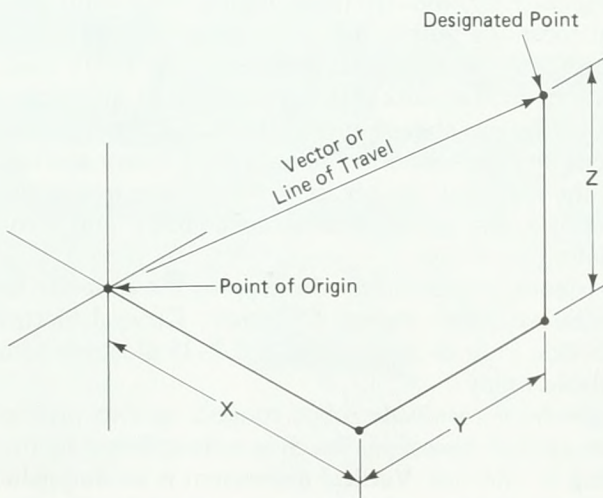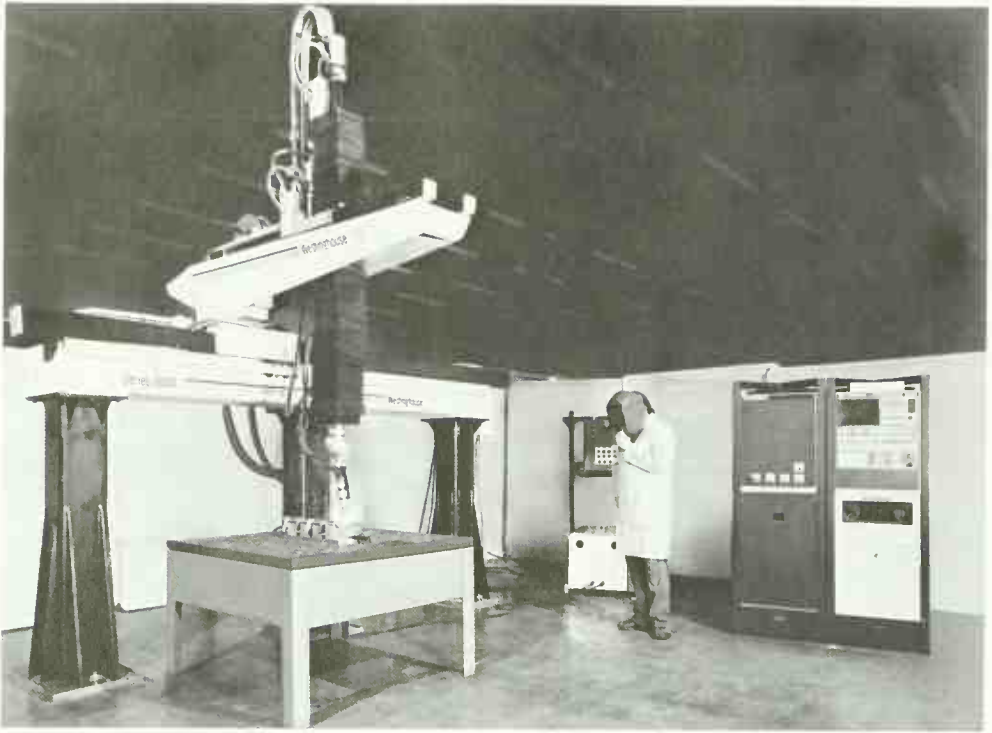**Figure 2–16.** Interpolation of joints in space.

Figure 2–17.   Westinghouse Series 6000 cartesian robot. (*Courtesy of Westinghouse Electric Corp.*)

load-carrying capacity, and dynamics of the robot are not greatly affected by different locations within the work space. Except for the XYZ geometry coordinate, most robots' arms are able to lift more weight at certain locations in the work space than at other locations. This is not true of the cartesian robot. The weight-lifting capacity does not vary with different locations. Robots that employ a rotary axis can be greatly affected by the inertia of the object when moving in a rotary direction. The subjects of dynamics resolution, repeatability, and accuracy will be discussed later in the text.

Some robot manufacturers who employ the cartesian arrangement are Westinghouse, IBM, Mobot, CyBotech, General Electric, and Advanced Robotics. Figures 2–17, 2–18, and 2–19 illustrate some cartesian robots available today.

The *cylindrical coordinate* robot consists of two orthogonal slides mounted on a rotary base axis. Reach is accomplished by the arm of the robot moving in and out. Vertical movement is accomplished by a carriage moving up and down a stationary post, or the post can move up
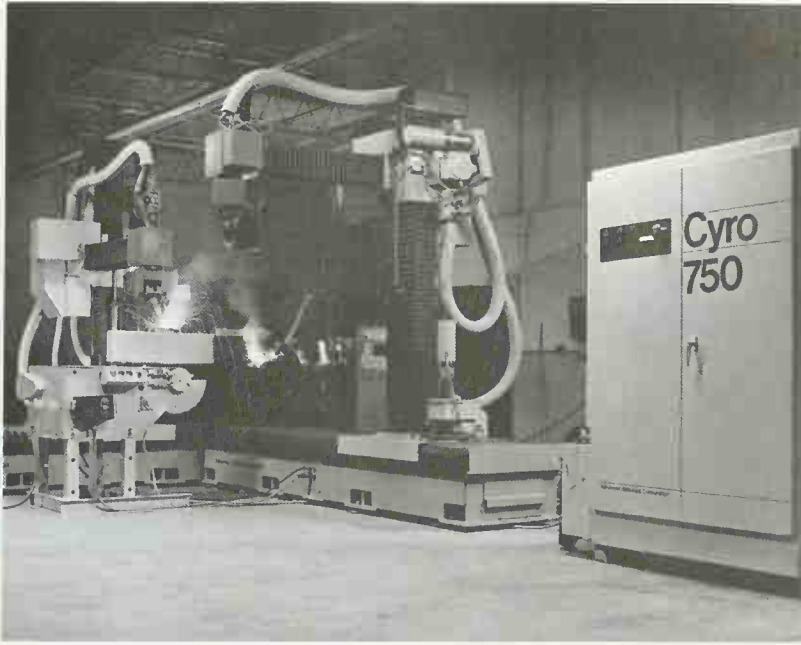
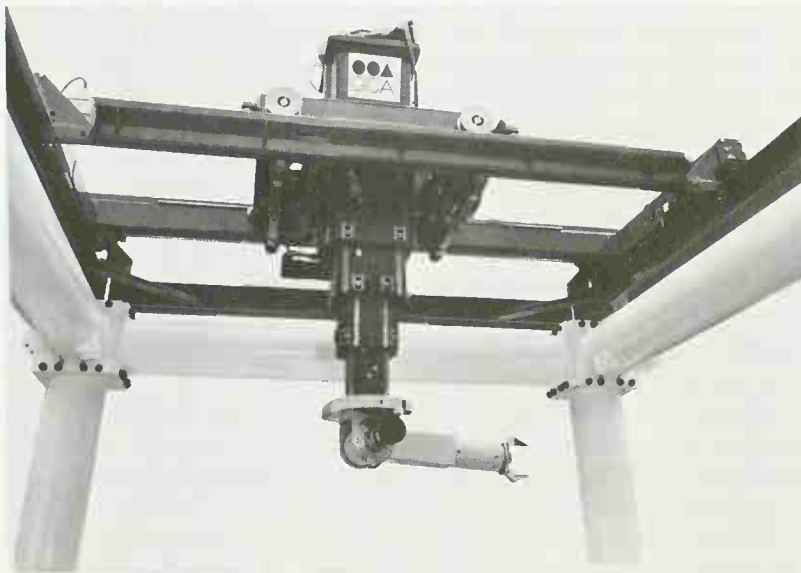**Figure 2–18.** Cyro 750 cartesian robot. (*Courtesy of Advanced Robotics Corp.*)

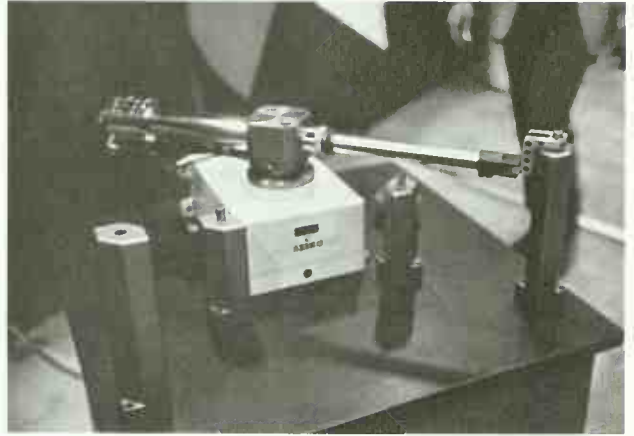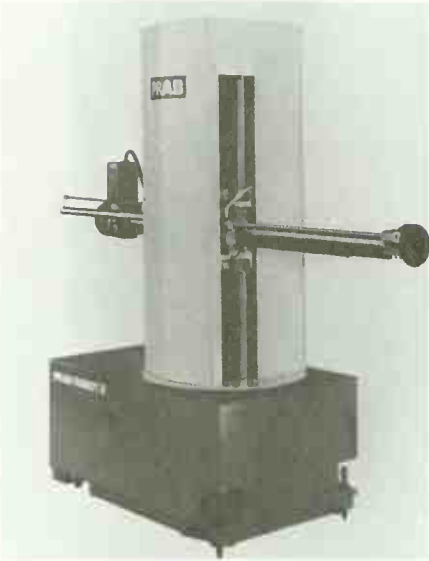**Figure 2–19.** GCA/XR™ Series cartesian robot. (*Courtesy of GCA Corp.*)

Figure 2–20.   (*Left*) Prab's Model "E" cylindrical robot. (*Courtesy of Prab Robots Inc.*)

Figure 2–21.   (*Right*) Seiko's 700 cylindrical robot. (Photo taken at Robot 7 show in Chicago.)

and down in the base of the robot. Prab's Model E robot employs the carriage arrangement, whereas Seiko's 700 employs the moving post (see Figures 2–20 and 2–21). The two linear axes rotate on the base. The three axes are capable of specifying points in a cylinder. Figure 2–22 is a line drawing showing the relationship of these three axes.

The selection of a certain configuration depends on the application of the robot. The jointed-spherical configuration is well suited for picking up parts or components at its base. The cylindrical robots are best employed when the points of delivery are located radially from the robot. However, the inertia of the part can play havoc with the position's accuracy if the rotary movement is at too great a speed. Also, inertia is affected by the extension or retraction of the horizontal axis. The effect of inertia is greatest when the arm is fully extended and least when it is fully retracted.

Several robots employ the cylindrical configuration. Some of the more noted manufacturers are Prab, Mobot, Anorad, Seiko, and Schrader Bellows. Figures 2–23 and 2–24 illustrate some cylindrical robots available today.

The *spherical robot configuration* resembles the turret on a tank. The robot has a pivot point which gives the robot its vertical movement. Reach is accomplished by a telescoping boom that extends and retracts.
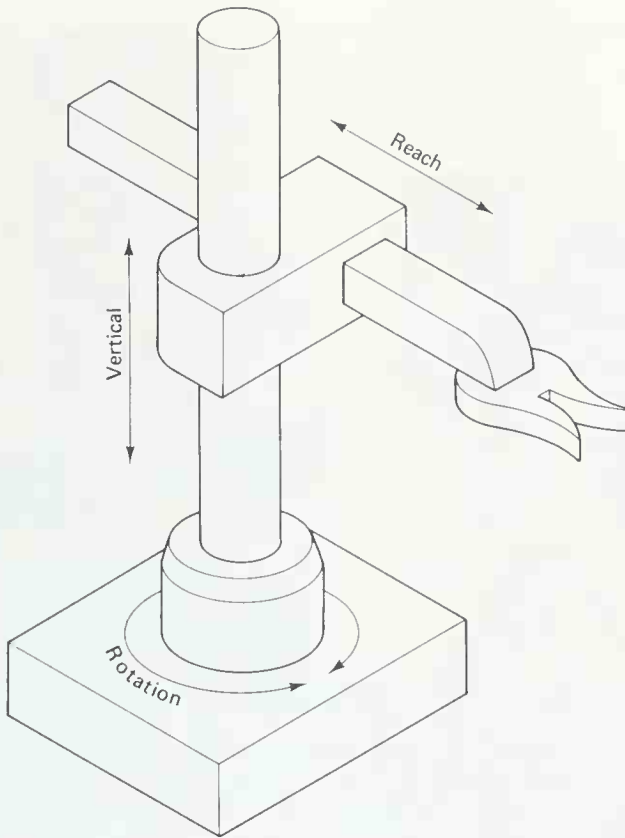
Figure 2–22.   Relationship of cylindrical robots.

Left-to-right movement is provided by a rotary axis. Figure 2–25 shows the movement of the three axes. The movement of the three axes approximates a work space of a sphere.

The spherical robot has some of the same problems as the cylindrical robot—inertia and spatial resolution. However, the problems associated with inertia can be resolved by reducing tool movement speed or by programming specific points for the tool to pass through on its move to a designated point in the rotary plane. Instead of the boom remaining extended in its rotary motion, the points can be used to retract the boom during its movement, thus reducing the effect of inertia on the rotary joint. The Snow Manufacturing cylindrical robot in Figure 2–26 illustrates this point.

The spherical robot is one of the oldest configurations employed by robot manufacturers. Westinghouse Unimation and Prab, two of the

Figure 2–23. (*Left*) Schrader Bellow Motion Mate Robot. (*Courtesy of Scovill, Schrader Bellows Division.*)
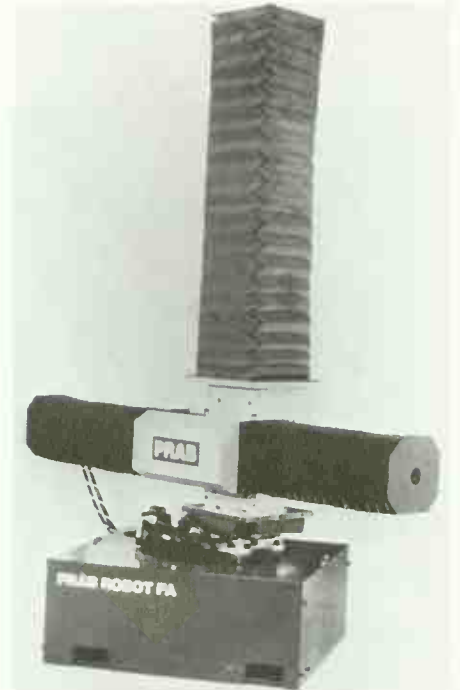**Figure 2–24.** (*Right*) Prab's FA cylindrical robot. (*Courtesy of Prab Robots Inc.*)

oldest robot manufacturers, have several spherical configuration models available today (see Figures 2–27 and 2–28). Other manufacturers that produce spherical models are United States Robots, Bendix, Armax, and General Electric.

In summary, the four basic robot configurations are the *jointed-arm*, the *cartesian*, the *cylindrical*, and the *spherical*. However, certain robot manufacturers may incorporate more than one configuration in a given model. The Reis robot model RR625/650 series is a unique combination of a cylindrical coordinate and a jointed-arm robot. This type of robot occupies a very small floor space, about the same space needed for a man or woman. The robot has an extended reach of 120 in. and a work envelope of 360° (see Figure 2–29). IBM's 7535 employs a combination of two different configurations. Although the IBM 7535 robot (Figure 2–30) is referred to as a jointed-arm robot, it can be considered jointed-cylindrical in operation. One expert refers to this arrangement as a *folded book.*
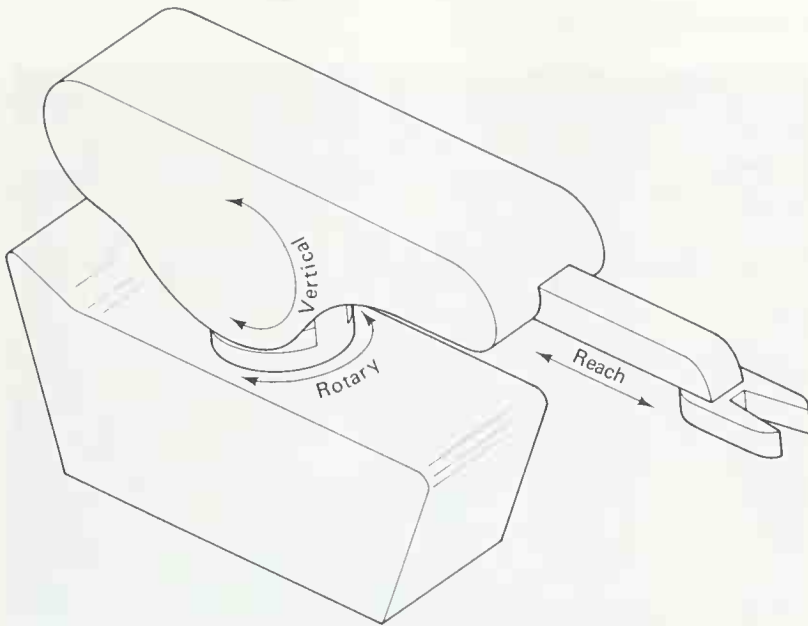
Figure 2–25. Axis movements of spherical robots.
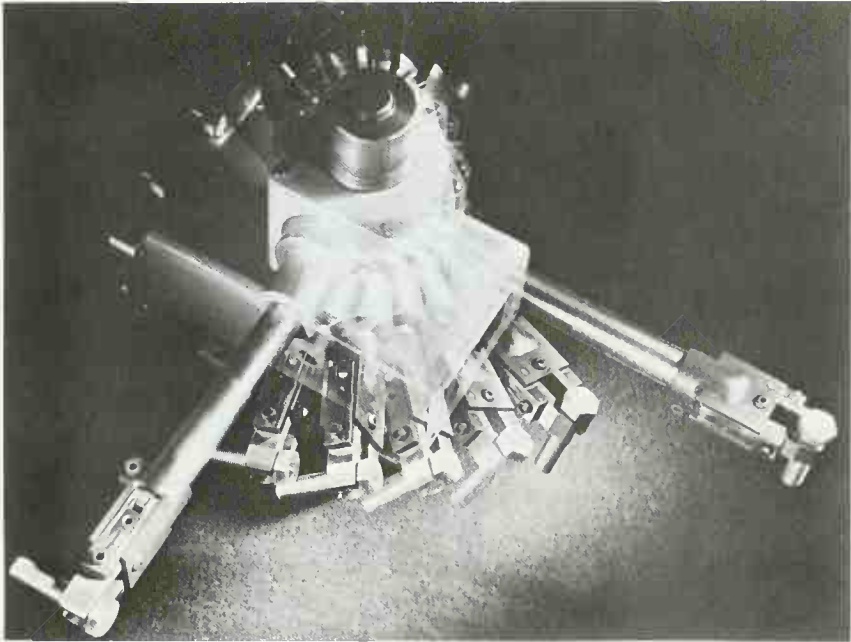
Figure 2–26. Illustration of boom being retracted and extended during the rotary movement. (*Courtesy of Snow Manufacturing Co.*)

33

Figure 2–27. Westinghouse's Unimate spherical robot. (Photo taken at Robot 7 show in Chicago.)

Figure 2–28. Prab's 4200 spherical robot. (*Courtesy of Prab Robots Inc.*)

Degrees of Freedom

Degrees of freedom can be defined as the way in which a body moves. For each degree of freedom, a joint is required. The degrees of freedom located in the arm *defines the configuration.* Each of the different motion

Figure 2–29. REIS-RR 625/650 Series cylindrical jointed-arm robot. (*Courtesy of Reis Machines.*)
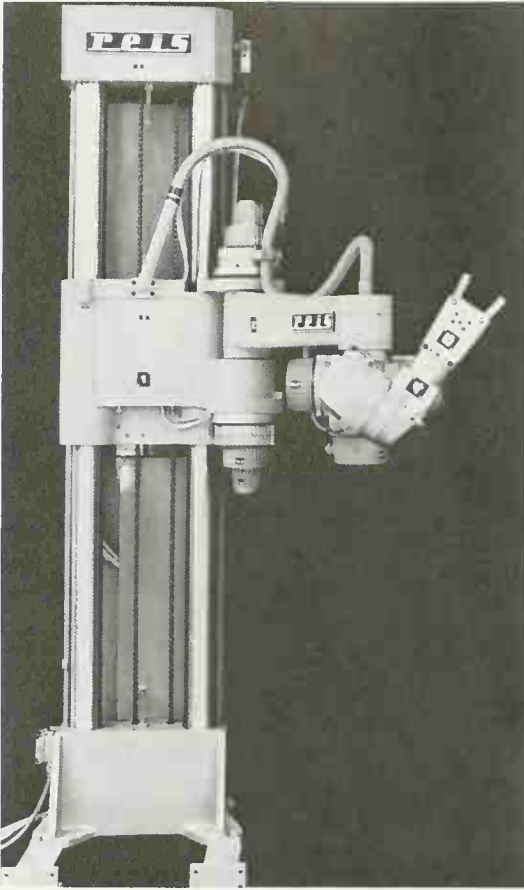
configurations previously discussed utilizes three degrees of freedom in the arm.

For applications that require a certain degree of flexibility, additional degrees of freedom are required in the wrist of the robot. Three degrees of freedom located in the wrist give the end effector its flexibility. Thus, a total of six degrees of freedom are needed to locate and orient the robot's hand at any point in its work space. Although six degrees are required for maximum flexibility, most robots employ three to five degrees of freedom. The more degrees of freedom, the greater the complexity of motions.
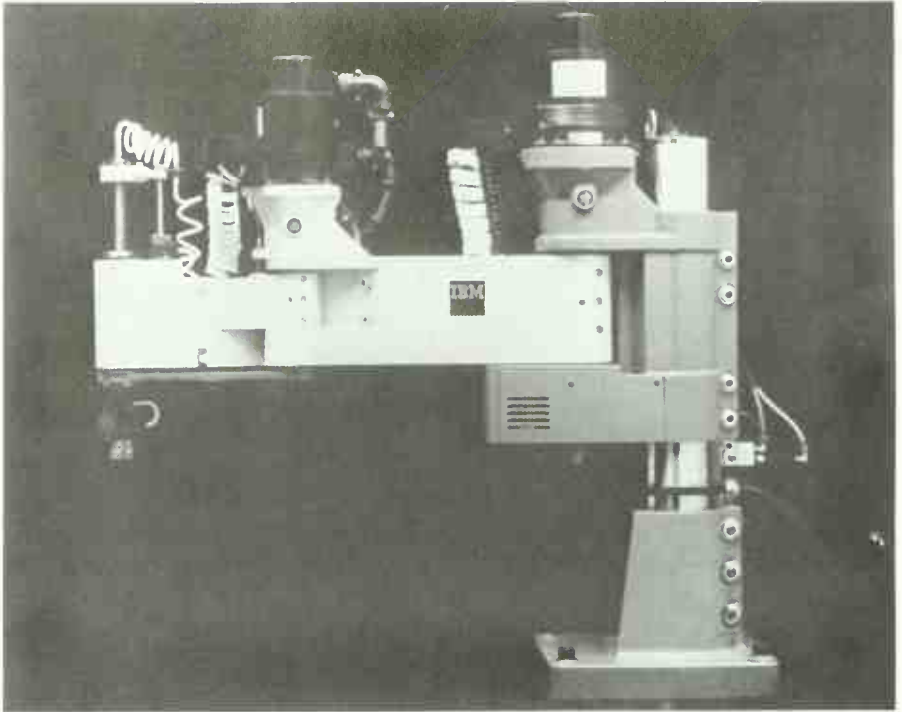
Figure 2–30. IBM's 7535. (*Courtesy of International Business Machines Corp.*)

Even though robots are considered to have a certain amount of dexterity, it is nothing compared to human dexterity. The movements of the human hand are controlled by *35 muscles*. Fifteen of these muscles are located in the forearm. The arrangement of the muscles in the hand provides great strength to the fingers and thumb for grasping objects. Each finger can act alone or together with the thumb. This enables the hand to do many intricate and delicate tasks.

The hand has *27 bones*. Eight bones are located in the wrist, 16 in the fingers, and 3 in the thumb. There are *22 degrees of freedom* or joints in the hand. Seven of these are in the wrist only. Figure 2–31 depicts the various bones found in the hand and wrist and their articulations.

From the line drawing in Figure 2–31 one can see that the hand is a very complex multipurpose tool. We use our hands to perform various repetitive tasks. But the bones-and-joint arrangement gives the hand the dexterity not found in machines. So if the movements of the robot seem rather awkward and clumsy, remember the robot is accomplishing these movements with only six degrees of freedom.

8 Carpals

5 Metacarpals

14 Phalanges

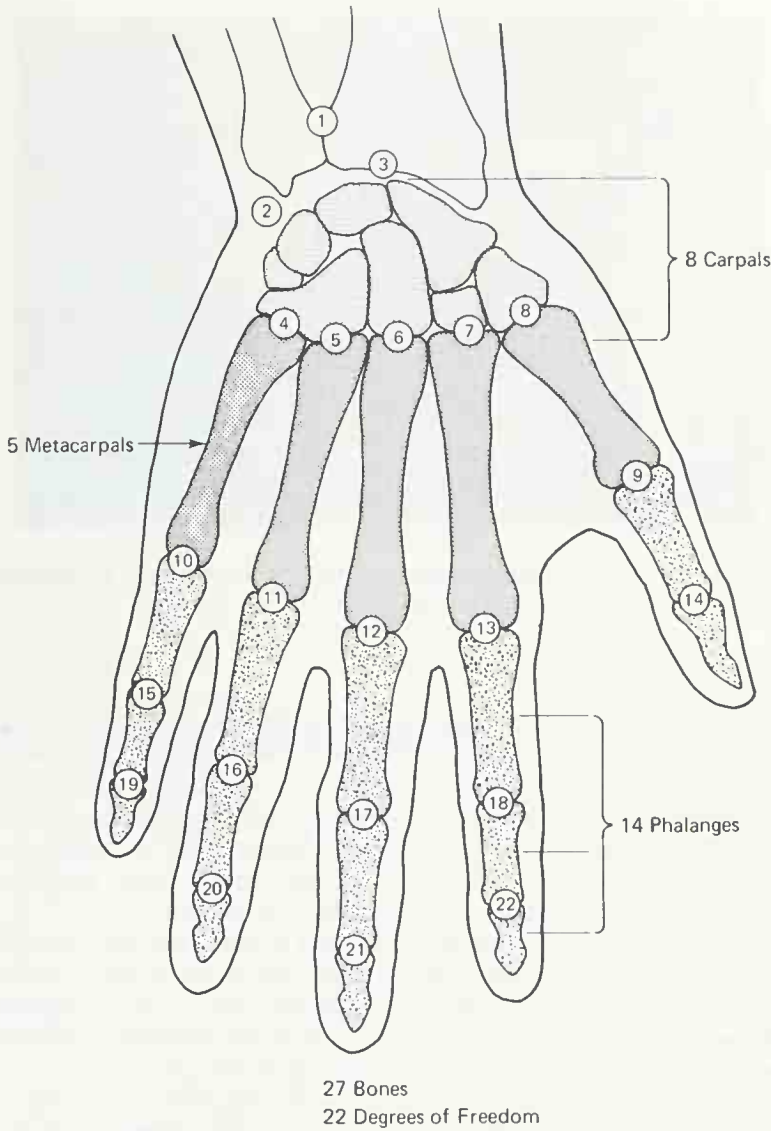27 Bones
22 Degrees of Freedom

Figure 2–31.   Bones and joints in the human hand.

Although some industrial robots have seven or eight degrees of freedom, there are six basic degrees. Three are located in the arm and three in the wrist. The other one or two degrees are achieved by mounting the robot on tracks such as the Prab model in Figure 2–32 which has a total of seven degrees of freedom.
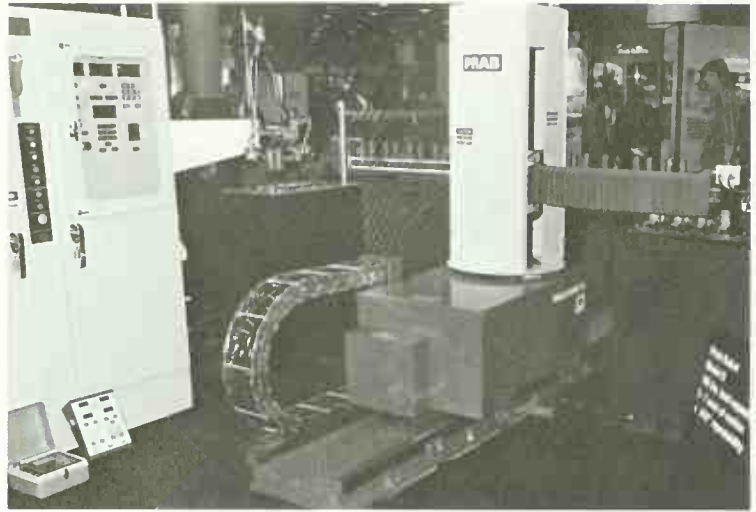
Figure 2–32. Prab's Model E robot mounted on a horizontal traverse track. (Photo taken at Robot 7 show in Chicago.)

The three degrees of freedom located in the arm are the *rotational traverse*, the *radial traverse*, and the *vertical traverse*. The rotational traverse has to do with the movement of the arm assembly about a vertical axis. This is the left and right swivel of the robot's arm about its base. The radial traverse has to do with the extension and retraction of the arm. This is the in and out motion relative to the base. The vertical traverse provides the up and down motion of the arm.

The three degrees of freedom located in the wrist bear the names of aeronautical terms: pitch, yaw, and roll. The *pitch*, or bend, is the up and down movement of the wrist; the *yaw* is the right and left movement of the wrist; and the *roll*, or swivel, involves the rotation of the hand. Figure 2–33 illustrates the six basic degrees of freedom.

Although the robot has only six major degrees of freedom, the range of movement in each joint is considerably greater than in the human being. The human hand has a bending range of approximately 165°, 90° palmar flexion and 75° dorsiflexion. The yaw movement of the wrist encompasses about 65°, approximately 20° in the direction of the thumb and about 45° in the opposite direction. The human wrist has a rotational range of approximately 150°. To better understand the range of movement in the human wrist, see Figure 2–34.

Even though the robot is quite clumsy in its movements, it does have an advantage over the human hand in the range of wrist movement. Figure 2–35 compares the six major degrees of freedom of the

1. Rotational Traverse

2. Radial Traverse

3. Vertical Traverse

4. Pitch

6. Roll

5. Yaw
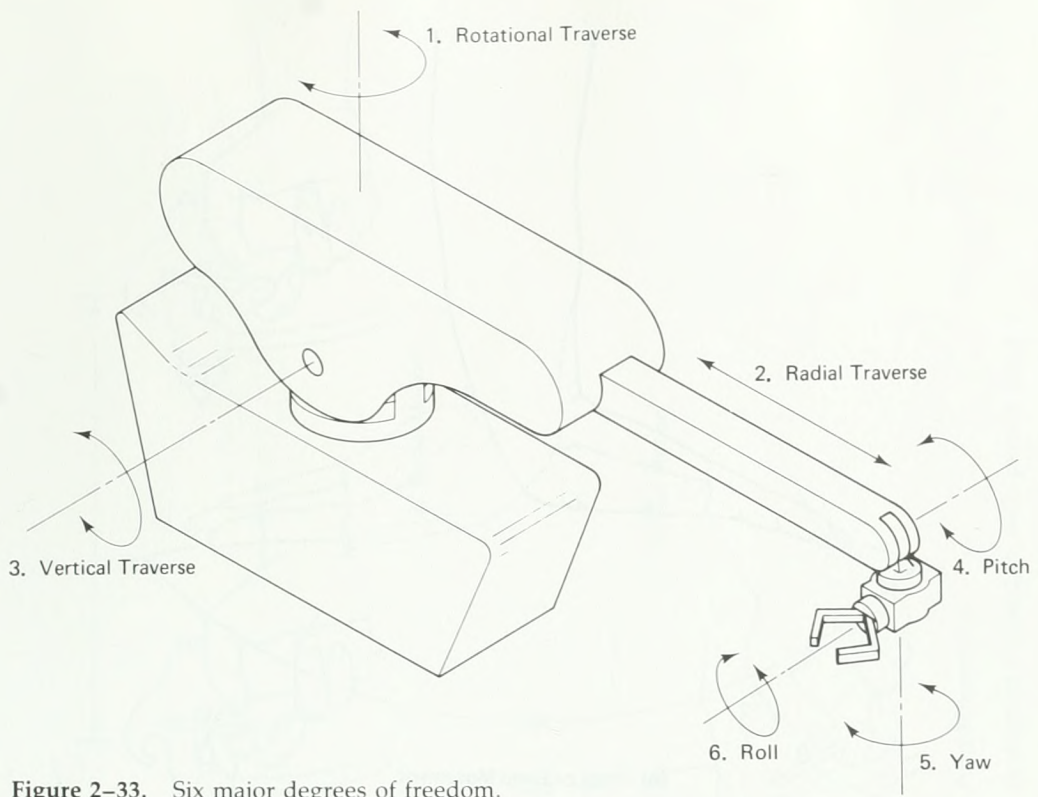
Figure 2–33. Six major degrees of freedom.

65°
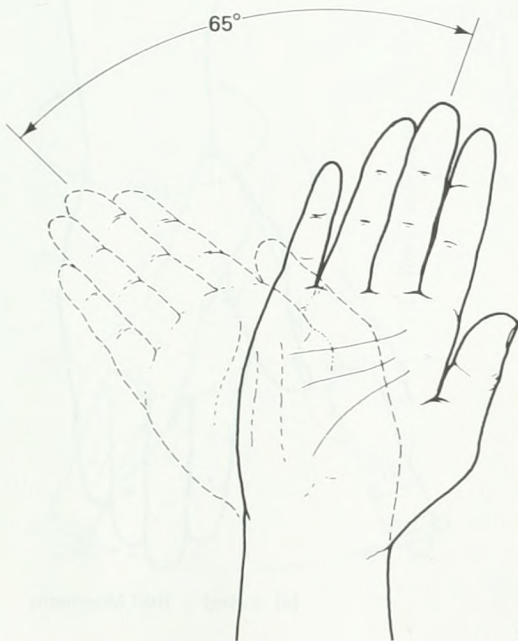
(a) Yaw Movement

Figure 2–34. Range of movements of the wrist.
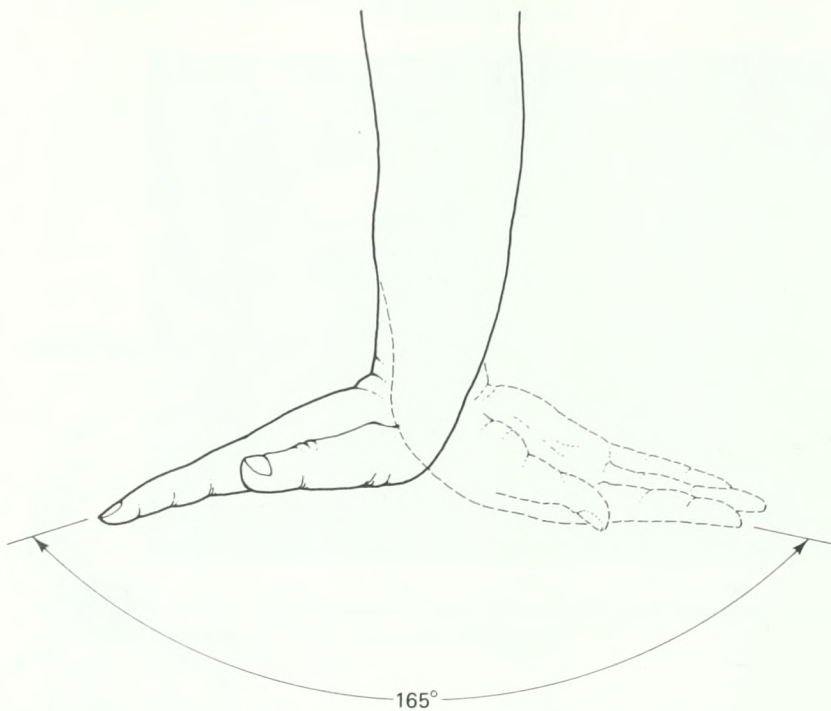
(b) Pitch or Bend Movement

(c) Swivel or Roll Movement

Figure 2–34 *continued*.

40

1. Rotational Motion

2. Radial Motion

3. Vertical Motion

(a) Arm Movements

Figure 2–35. Comparison of the six degrees of freedom with person using a spray gun.

41

4. Yaw

(b) Wrist Movements

5. Pitch

Figure 2–35 *continued.*

42
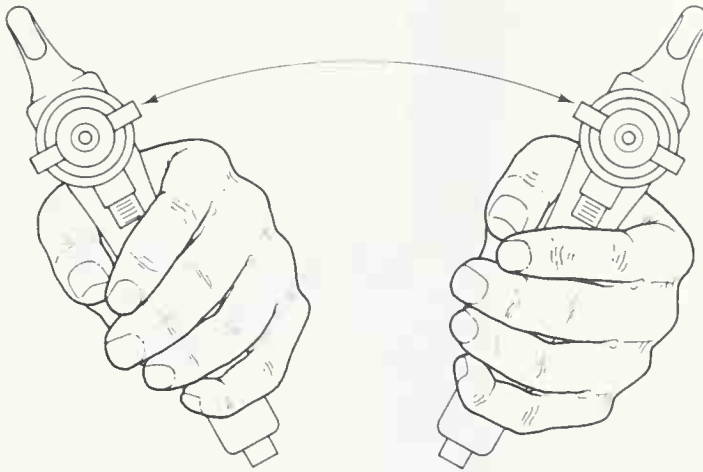
6. Roll

(b) Wrist Movements

Figure 2–35 *continued.*

robot with that of a person using a spray gun. This example provides a better understanding of the movements of the robot's arm and wrist.
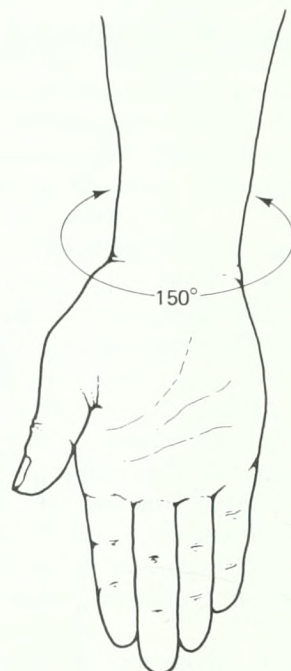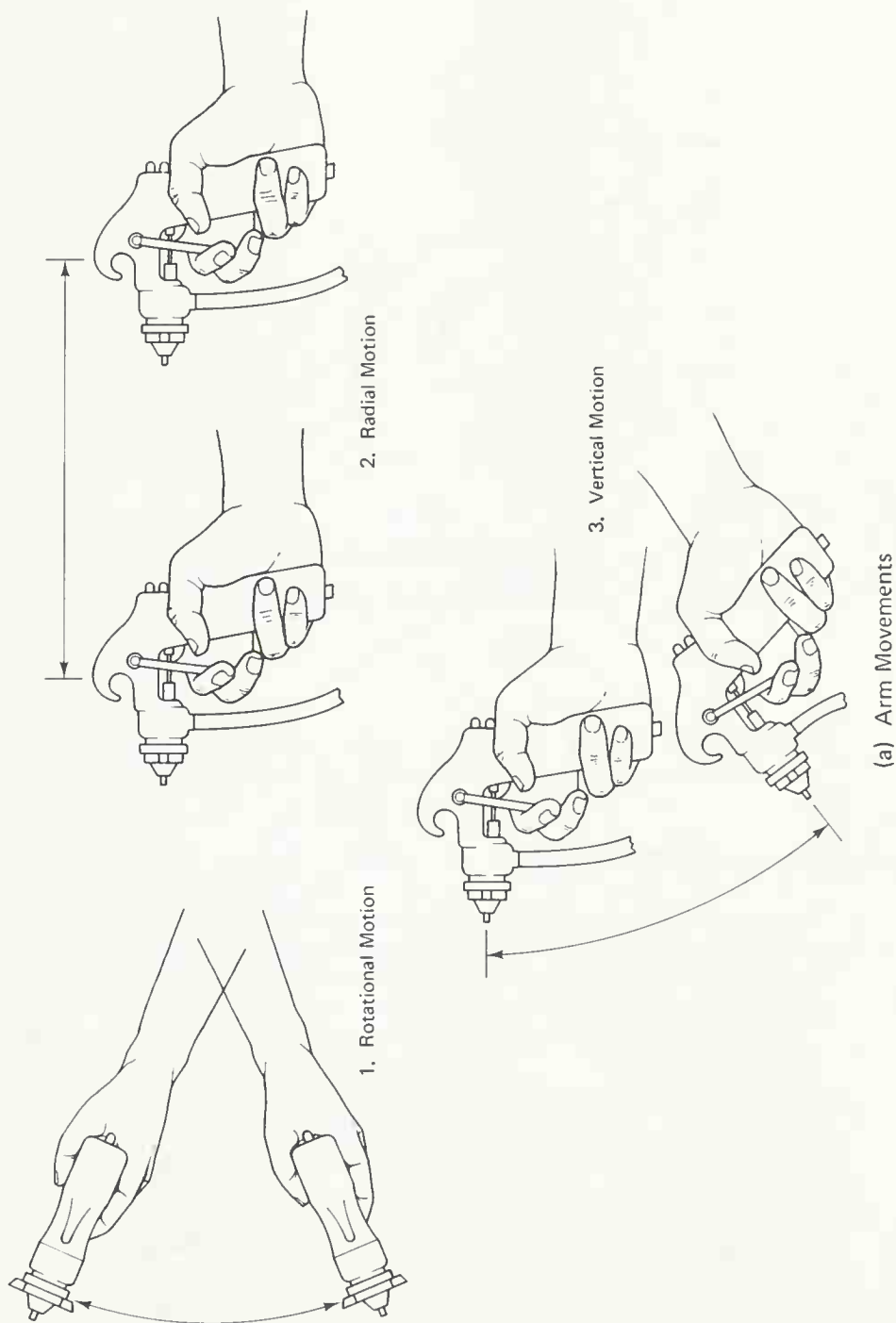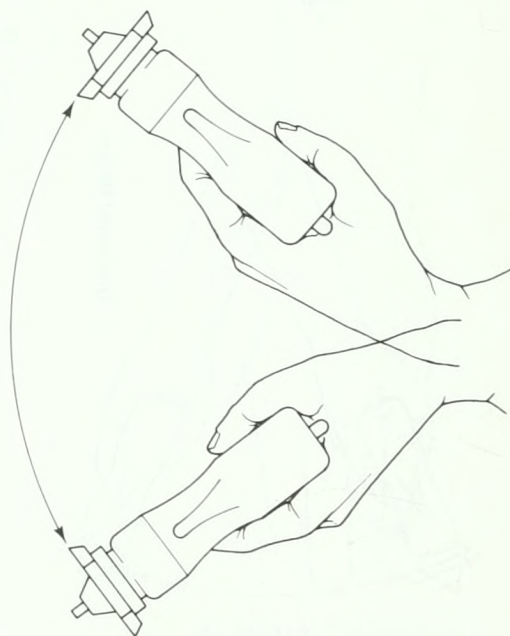
Work Space or Work Envelope

One of the most important characteristics to consider when selecting a robot is the work envelope. An examination of literature from various robot manufacturers will reveal that the term *work envelope* is not universally used. Some common interchangeable terms are *work space, work volume, operational range,* and *work range*. For the purpose of our discussion we shall use the term *work envelope*.

The work envelope can be defined as the region the robot's hand is capable of reaching in all directions. To identify this maximum reach, a point on the robot's wrist is used rather than the tip of the gripper or the end of the tool bit. So, in essence, the work envelope is slightly larger when the tip of the tool is considered.

The work envelope can be increased by mounting the robot on a moving base. Figure 2–36 shows a Reis 625 robot mounted on a horizontal traverse. This type of arrangement can provide the robot with an extra degree of freedom and enables the robot to service more than one work station.
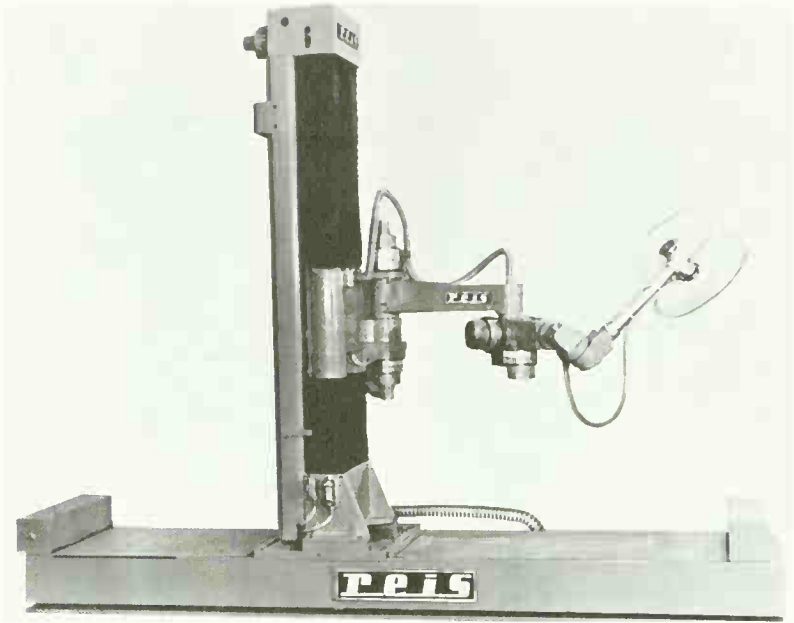
Figure 2–36.   Reis RR 625 robot with seventh axis traversing base. (*Courtesy of Reis Machines.*)

The arrangement of the joints and the length of segments in the manipulator determine the shape of the work envelope. The different work envelopes are generally identified by the various geometric shapes the robot's arm is capable of duplicating. The points that the cartesian coordinate robot is capable of reaching in all directions generates a work envelope in the *shape of a rectangular box*, whereas the cylindrical coordinate robot approximates a work envelope the *shape of a cylinder*. The work envelope of the spherical robot closely resembles the *shape of a sphere*.

Some robot work envelopes do not resemble one single geometric shape. This is true of the jointed-spherical or revolute coordinates. The shape of the work envelope can best be described as *irregular*. Figure 2–37 shows some of the different shapes of work envelope generated by various robots today.

REVIEW QUESTIONS

1. The industrial robot consists of three major components. Name the three components and explain the purpose of each.
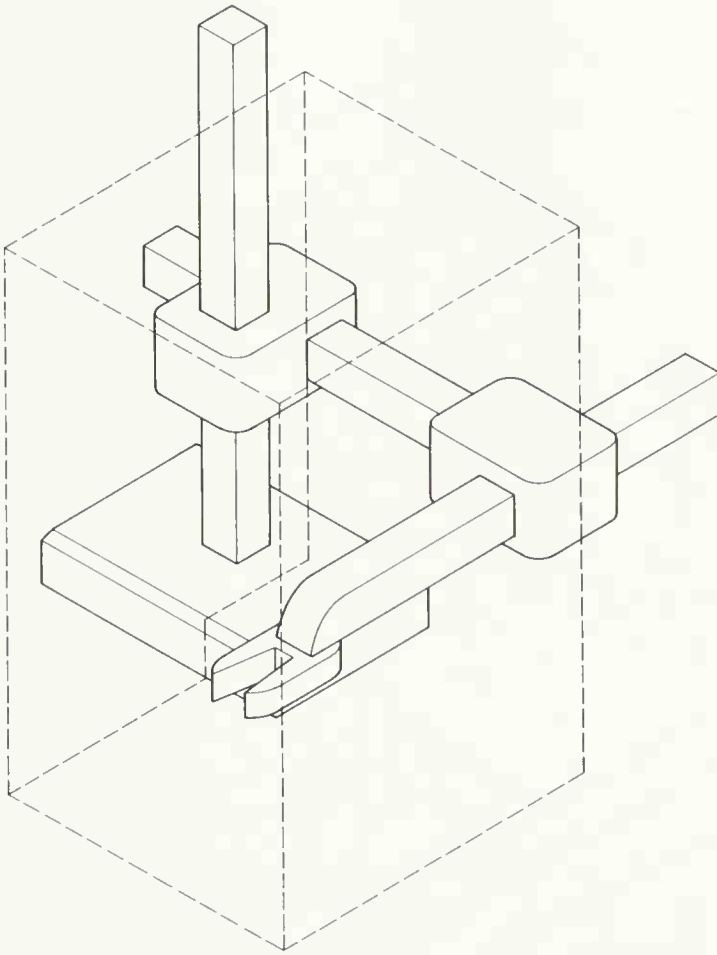
(a) Cartesian Coordinates

Figure 2–37. Different work envelopes.

2. Some robots are considered anthropomorphic. What does the term *anthropomorphic* mean?
3. What is the technical name for the robot's hand?
4. The manipulator of the robot may include such components as actuators, control valves, and internal sensors. Briefly explain the purpose of each.
5. Name the three power supplies used on robots today. Cite advantages and disadvantages of each.
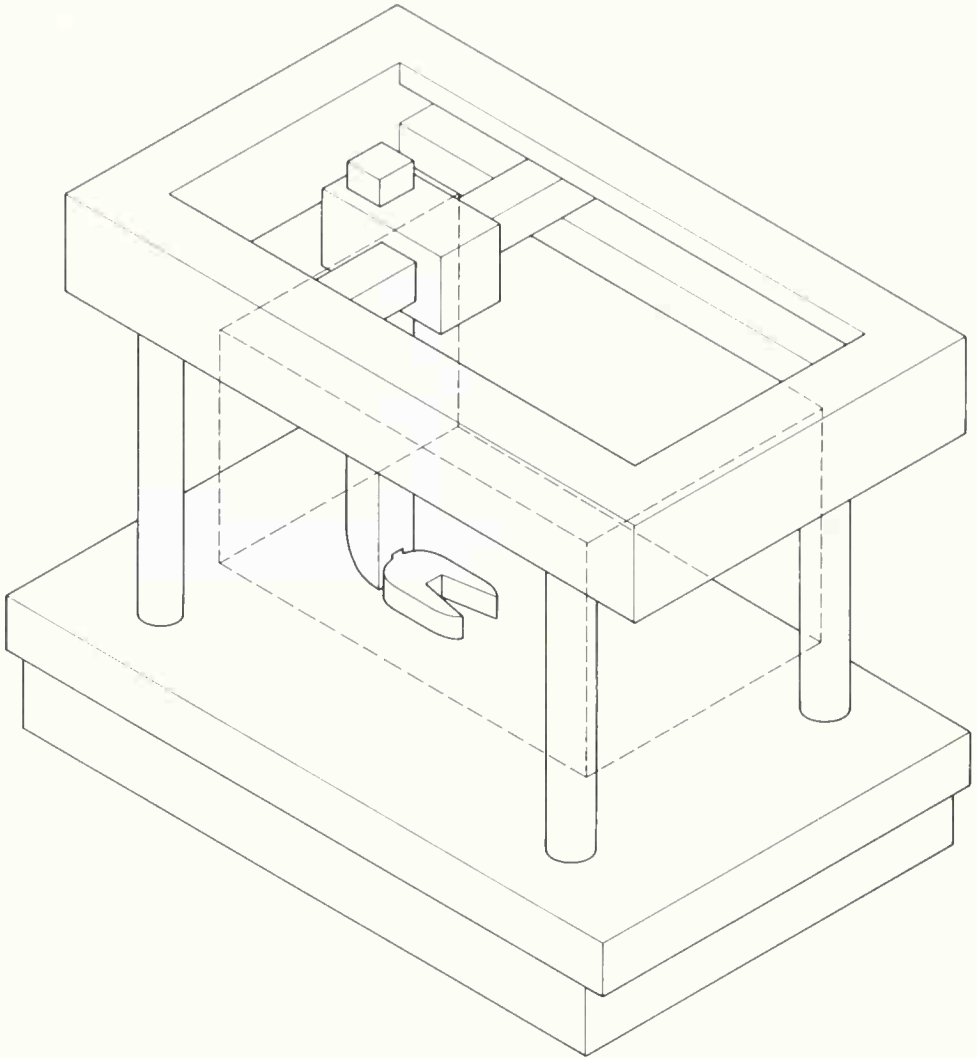
(b) Cartesian Coordinates

Figure 2–37 *continued.*

6. Controllers can vary in complexity and capability. Give an example of a low-level controller and a sophisticated controller.

7. List and explain the different Japanese and American classifications of robots. After comparing each classification, specify which of the Japanese classifications are not considered robots according to the U.S. definition.
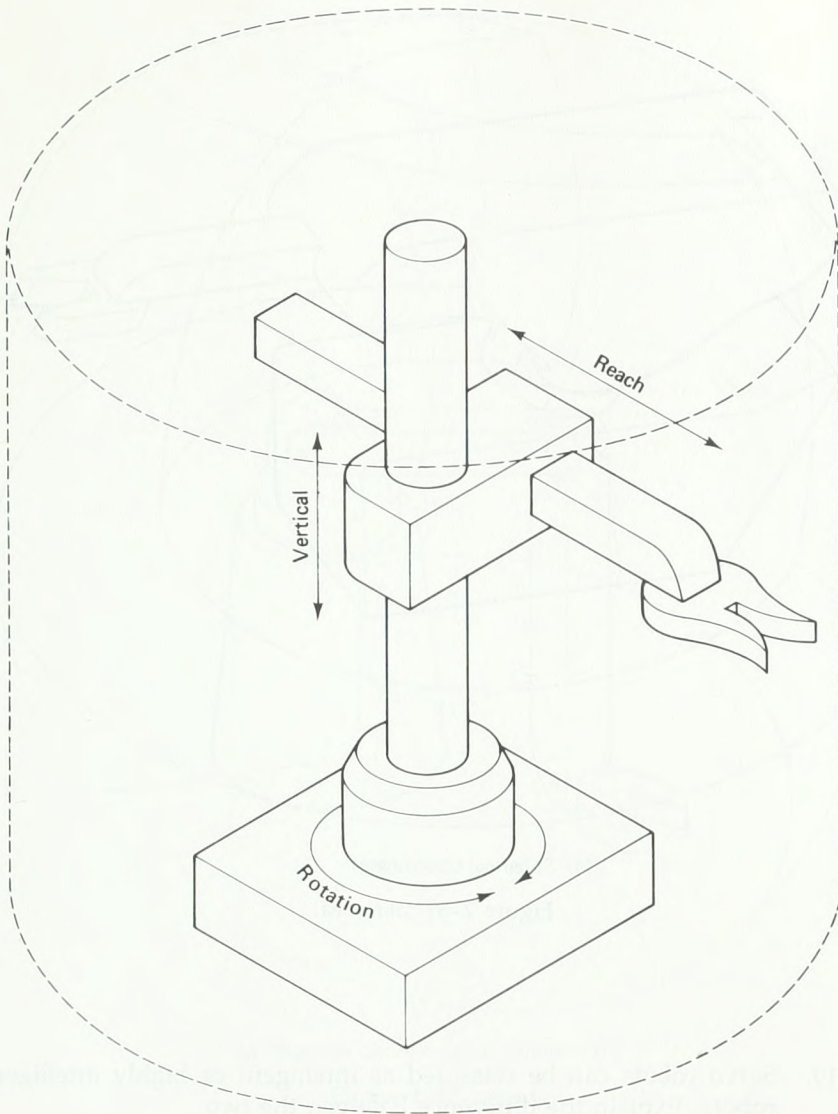
(c) Cylindrical Coordinates

Figure 2–37 *continued.*

8. Nonservo robots are considered open loop. What does the term
   open loop mean?

9. Servo robots are considered closed loop. Sketch a diagram of a
   servo robot and explain how the servo robot works.
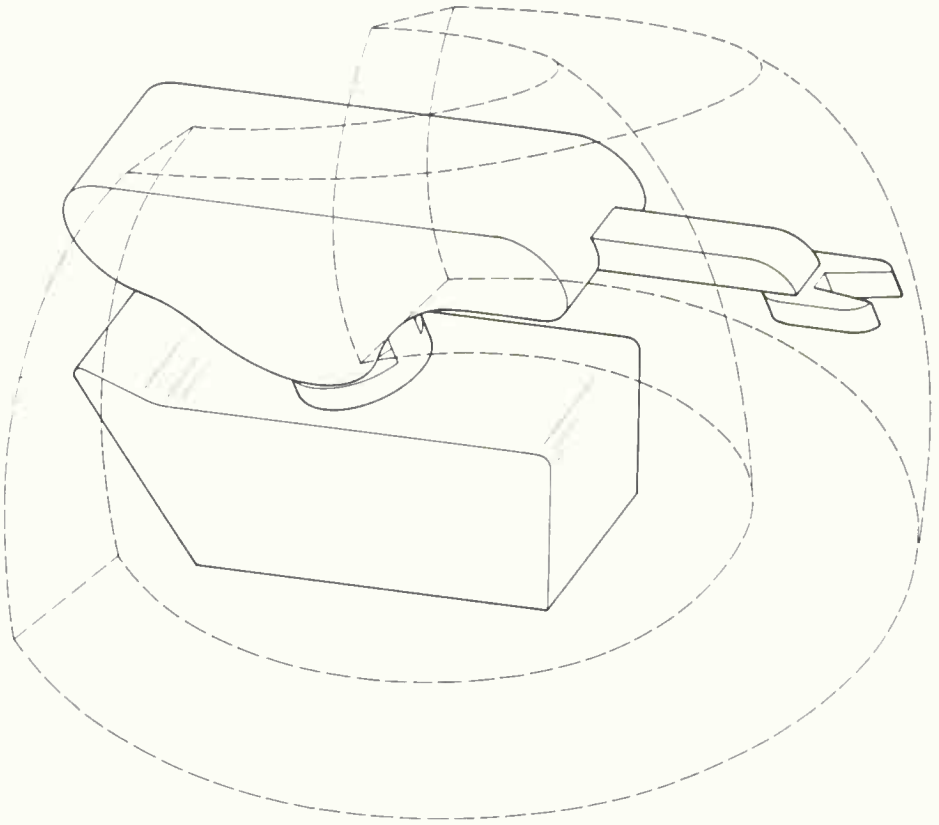
(d) Spherical Coordinates

Figure 2–37 *continued.*

10. Servo robots can be classified as intelligent or highly intelligent robots. Explain the difference between the two.

11. Robots vary in shape and size. What are the four basic configurations of a robot? Which configuration is most common?

12. What are some advantages of the cartesian coordinates over the other configurations?

13. Give two examples of robots that employ a combination of configurations.

14. Robots may have seven or eight degrees of freedom. How many degrees of freedom are in the human hand and wrist?
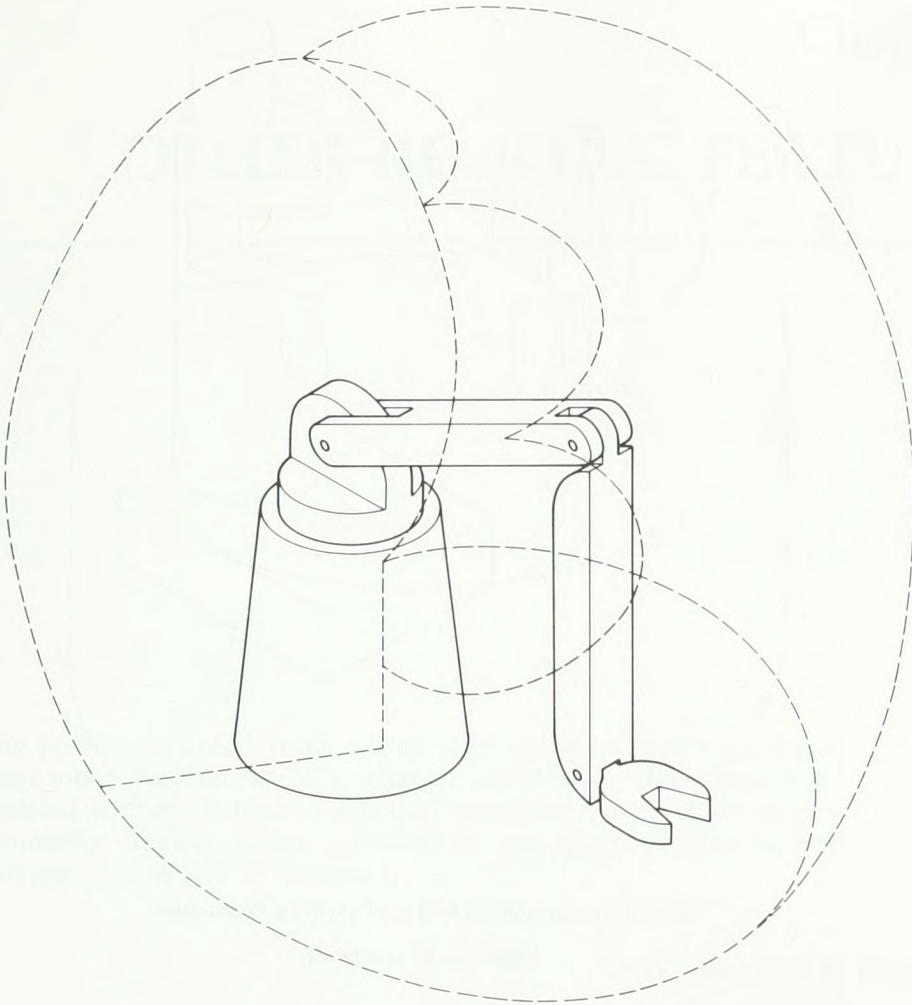
(e) Revolute Coordinates or Jointed-Arm

Figure 2–37 *continued.*

15. List and explain the six basic degrees of freedom used on robots.
16. Define work space or work envelope.
17. What are the four common work envelopes employed by robots?
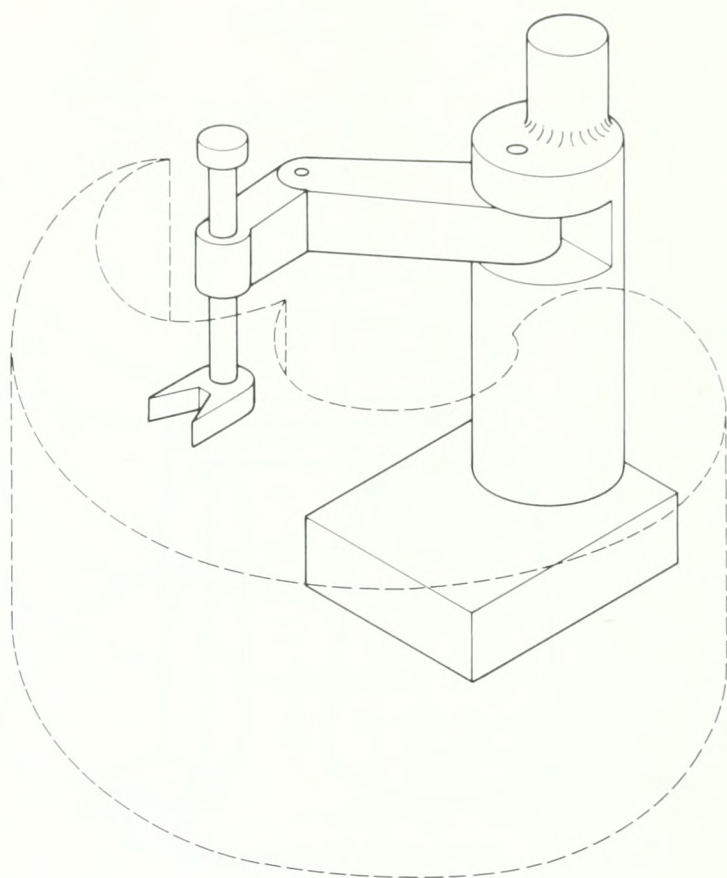
(f) Combination Jointed-Arm and Cylindrical Coordinates

Figure 2–37 *continued.*

OTHER ROBOTIC FEATURES

The previous chapters dealt mainly with historical development and basic robot characteristics. This chapter will examine other features associated with the subject of robotics. Topics such as methods of programming, motion control, performance measures, end effectors, and external sensors will be discussed.

Methods of Programming

For all practical purposes the programming of robots falls into four major categories: manual, lead-through, walk-through, and software programming. Although these are the major methods of programming robots, the area of voice and two-way communications is also being explored today. Voice programming will be covered as well. Figure 3–1 shows examples of these various methods of programming.

Manual programming can best be described as a machine setup. Programming is accomplished by an operator physically setting the necessary end stops, switches, cams, electric wires, or hoses to complete a set sequence of steps. This type of programming is characteristic of the less sophisticated robots known as *limited-sequence* or *pick-and-place* robots. Even though these robots are regarded as rather simple in nature,

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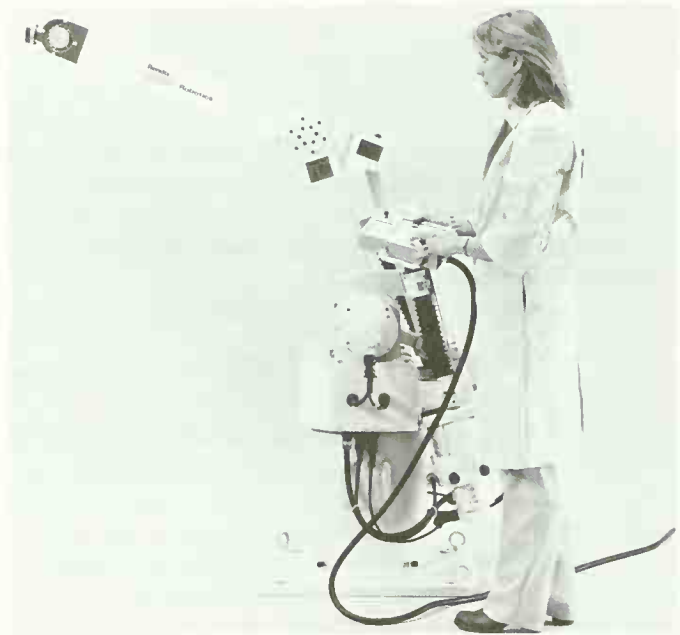

(b)

(c)

Figure 3–1. (a) Manual programming—operator manually adjusts necessary end stops, switches, cams, etc. (b) Walk-through programming—operator physically moves the robot's arm and hand through their movements. (Photo taken at Robot 7 show in Chicago.) (c) Lead-through programming—operator uses teach pendant to step the robot through the various moves. (*Courtesy of Bendix Corp.*)

(d)

(e)

Figure 3-1 (*continued*) **(d)** Software or off-line programming—involves the preparation of a program by means of a computer language. **(e)** Voice programming—voice recognition is accomplished by having an operator speak a phrase several times to determine voice frequency.

they are capable of performing many of the tasks found in manufacturing. If an application is suited for the less sophisticated robot, there is no reason to invest in one of the more complex models. A general rule to follow is to avoid purchasing more robot capabilities than those needed for the particular application.

Lead-through programming is where the operator uses a teach pendant to lead the robot through the various desired positions or locations; as the robot's hand reaches each desired point in the sequence of motion, the point is recorded into memory. The points recorded in memory are used to generate the path the robot follows during operation.

The lead-through method of programming is a popular method of programming. It is rather easy and convenient for programming a lot of tasks found in industry. However, if the operation is complex or positioning tolerances are close, the time required for programming may increase substantially.

Walk-through programming is utilized on the playback robots. Usually an experienced operator physically moves the robot's hand through the desired motions. While the operator is moving the robot through the desired path, various points are sampled and recorded into memory for later playback. A single program may consist of several thousand

points. Since a large number of points is involved in a single program, magnetic tape or a floppy disc is generally used to store programs.

The number of times the robot samples points may vary from one manufacturer to another. The Nordson coating robot samples 32 times per second. The DeVilbiss Trallfa robot samples 80 times per second. As the number of points is increased, the movement of the robot becomes more fluid or smoother. Also, as the number increases, so does the need for greater storage capacity.

Spraying and arc-welding applications are the most common applications for walk-through programming. Other applications that employ walk-through programming are grinding, deburring, and polishing. Some manufacturers even use this method of programming for palletizing materials.

Software programming involves the programming of the robot by means of a computer. This method of programming is also known as off-line programming since the programming generally occurs away from the robot.

The program is prepared in a high-level language. The first robot programming language, known as WAVE, was developed at the Stanford Artificial Intelligence Laboratory in 1973. The language was developed for research purposes rather than for manufacturing applications.

Most robot manufacturers that provide off-line means of programming have developed their own proprietary language. This has been due to the lack of standards in the robot industry. Some common languages founded in the robot industry are AML (IBM), HELP (General Electric), VAL (Unimation), AL (Stanford University), RAIL (Automatix), and MCL (McDonnell Douglas).

Off-line programming does have certain advantages over the other methods of programming. The computer provides greater flexibility. The high-level languages enable the robots to carry out complex operations. Also, programming time can be reduced. Another advantage of off-line is that the robot does not have to be taken out of service during reprogramming. The reduction in programming time and increased utilization of the robot enhance the robot's productivity.

Voice programming has mainly been regarded as a novelty. But as the state of the art increases and cost decreases, its utilization is certain to grow.

Voice programming employs the use of a voice recognition device. Voice recognition is accomplished by having an operator read or repeat a phrase of words several times. After this is completed, the electronic equipment computes the average voice frequency of the operator. Recognition of the person's voice is determined by the voice frequency. Experts say that voice identification is just as accurate as the use of fingerprints for identification purposes.

After voice recognition is accomplished, the robot will respond to the operator's voice in carrying out those commands it has been programmed to do. From the previous discussion it is evident that the robot will respond only to the commands of the voice it has been taught to recognize. If a different operator is used, the robot has to be taught to recognize his or her voice. The recognition device may have trouble if the operator has a cold or sinus problem.

Voice recognition devices are commercially available today. Voice programming is being taken seriously in areas dealing with the physically handicapped. Voice programming has been successful in working with quadriplegics. Probably one of the biggest hindrances has been the cost of the equipment. The cost of a robot with voice communication that can work with the handicapped will run in excess of $50,000. Also, there must be two-way communication in working with quadriplegics. The robot must be able to recognize the user's voice and verbally repeat the commands before carrying them out. When voice programming is used for other applications, the procedure of having the robot repeat the commands is also employed to avoid possible damages and injuries.

There are certain advantages that make voice programming attractive. Verbal communication is a cheap means of communication. If the user is totally paralyzed, voice control is the only means of communication. Voice programming can reduce programming time and operator anxiety. Since manufacturing trends are shifting from part volume to greater part variety, reduction in setup time and programming time is a must. The operators may be a little reluctant to use some of the other programming methods, but with voice programming that fear is reduced. Voice programming can truly be described as a *user friendly* method of programming.

In the future, voice communication from the robot will probably be used to warn the operator or supervisor of possible problems in an operation. Voice communication could also be used for robot diagnostic purposes. If the robot is experiencing trouble with one of its components, the trouble could be verbally communicated to the service person.

Motion Control

Closely related to the method of programming is the motion control of the industrial robot. For all practical purposes the robot's end effector moves to or through a sequence of points. For the purpose of this text three classifications concerning patterns of motion will be considered. The three classifications are pick-and-place motion, point-to-point motion, and continuous-path motion.
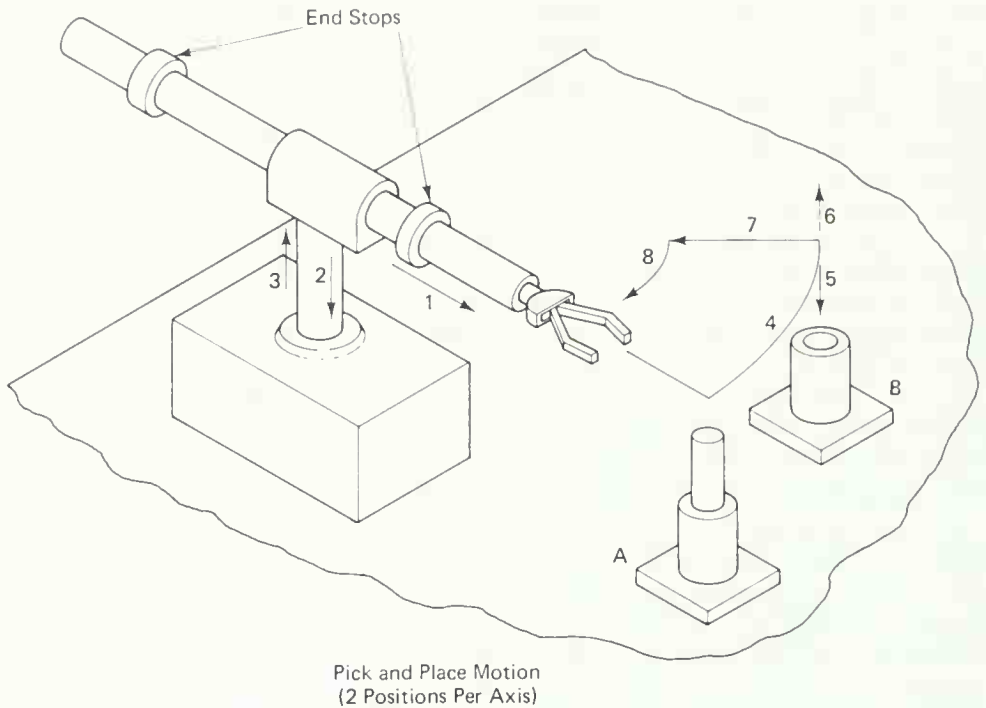
Figure 3–2.   Pick-and-place motion (two positions per axis).

Limited-sequence robots use pick-and-place motion. *Pick-and-place motion* can be regarded as a limited point-to-point motion. That is, the number of points the robot is capable of duplicating are rather few in number. Fewer points are involved because programming is accomplished by manually setting mechanical stops, limit switches, etc. In order for the robot's end effector to arrive at some designated point, end stops on the various axes have to be adjusted. Each axis has two positions to control the length of travel. It is possible to have more than two positions per axis, but the extra controls needed to accomplish this feat are not worth the effort.

The movement of the end effector of a limited-sequence robot from one position to another follows a fixed or set order. And generally only one axis of the robot moves at a time. Figure 3–2 shows a possible pick-and-place motion sequence. Even though it is point-to-point motion, the positioning points are along the various axes rather than as points in space.

Point-to-point (PTP) *motion* involves the movement of the robot through a number of discrete points in space. (See Figure 3–3.) The programmer uses a combination of the robot axes to position the end effector at a desired point. Those positions or points pertinent to the
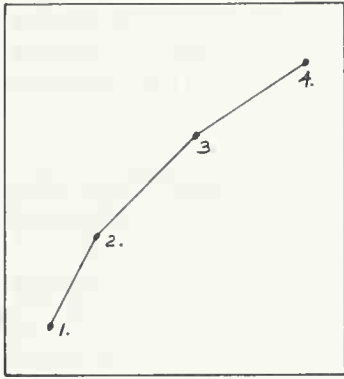
Figure 3–3.   Point-to-point motions (discrete number of points in space).

program are recorded and stored in memory. During the playback mode the robot steps through the points recorded in memory. The path of motion is a straight line between the recorded points. Just as in pick-and-place motion, point location is more important than controlling the path of travel.

During the playback mode the trajectory of the robot's end effector in PTP is generally different from the path used by the operator to move the end effector from one point to another. This is due primarily to the operator independently moving each axis or joint of the robot during programming. However, if a joystick is incorporated during programming, an interpolation of the arm axes can be performed, thus causing the robot to move in more of a straight path between points. The joystick can help reduce programming time.

Point-to-point positioning servo robots are capable of storing hundreds of discrete points in space. Several stops along a given axis can be accomplished rather than the two stops in pick-and-place motion. Acceleration and deceleration can be controlled between points by using a device such as a tachometer on the various axes.

In order to better understand point-to-point motion control, let us use the simple example given for pick-and-place motion in Figure 3–2. The task will be to take a peg out of a holder and insert it into another holder at a different location. Instead of using end stops to control lengths of travel, the desired point locations will be recorded into memory.

The setup consists of a peg being located in a holder at station A. The robot's arm is retracted and the gripper opened. Point of insertion is at station B. The steps are as follows:

1. Move the robot arm until the gripper is located above the peg and record the point.
2. Adjust the wrist joints of the robot until the gripper is properly aligned for grasping the peg. Record this position into memory.

3. Move the robot's gripper down over the peg where the gripper will be able to grasp the peg when closed. Realign the gripper with the peg by adjusting the various joints. Record this point into memory.

4. Close gripper on peg and record point.

5. Carefully remove the peg from the hole in a vertical direction. After peg has been sufficiently removed from the hole and is at its desired elevation, record that point into memory.

6. Move the robot's arm until it is approximately over the center of the hole at station B. Record this point into memory.

7. Carefully lower the peg and adjust the various joints until peg is freely inserted into hole in the proper attitude. Record this point into memory.

8. Open gripper to release peg and record point.

9. Move the robot arm until the gripper is located at some point directly above the peg and record this point.

10. Stop robot and place peg back in hole of station A.

11. Take the robot out of the teach mode and press play button.

The robot will return to its original start position and will step through the various points recorded into memory. The robot will have to be stopped after step 9 in the program because it has no way of knowing the absence of the peg at station A and the presence of it at station B. In order to eliminate this problem the program could be extended to include the movement of the peg back to its original location.

Continuous-path (CP) *motion* can be regarded as an extension of point-to-point motion. The difference is that continuous path involves the utilization of more points. A continuous-path program can have several thousand points. Since more points are used, the distances between points are extremely close. (See Figure 3–4.) Due to the large number of points, the robot is capable of producing smooth movements that give the appearance of continuous or contour movements.

Continuous-path motion is concerned more with control of the path movement than with end point positioning. The unit generally does not come to rest at various points in the program, as is often required in PTP.

Programming of the path of motion is accomplished by an operator physically moving the end effector of the robot through its path of motion. While the operator is moving the robot through its motion, the position of the various axes are recorded on some constant time frame. Some continuous-path robots record up to 80 points per second. Programs are generally recorded on magnetic tape or magnetic disc. A program may last several minutes.
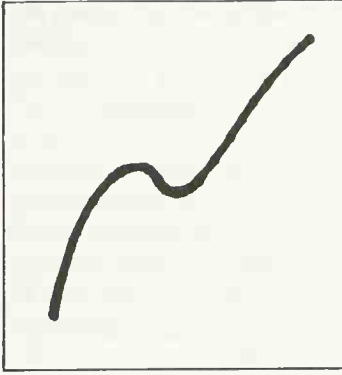
Figure 3–4. Continuous-path motion (infinite number of points).

After the movements of the robot have been recorded on magnetic tape, the playback speed of the tape can be changed to provide the best operation speed for the task. For certain applications it may be better to program the robot at a slower speed and use a faster playback speed. Other applications require faster programming speeds than play-back speed. Two examples where this may apply are spraying and arc welding.

It is evident that continuous-path control does offer certain advantages. More complex and smoother moves can be accomplished by continuous path. Programming is rather simple and no knowledge of programming is required. All that is required is that the operator be knowledgeable of the operation he or she is trying to teach the robot to duplicate.

Just as there are certain advantages to using continuous-path motion, there are certain disadvantages. In order for the controller to store all the points, a large memory is required. As is apparent, as the size of memory increases so does the cost. Another disadvantage lies in the area of programming. Since the positions of the various axes are sampled on a constant time frame, the undesirable motions as well as the intended moves will be sampled and recorded into memory. The robot will duplicate all these moves during the playback period.

Another point of consideration is that the robot's arm must be counterbalanced and able to move freely without power. This is a must if the operator is to produce smooth-flowing moves.

Performance Measures

Up to this point in the text several things have been discussed that one must consider when purchasing a robot: types of configuration, types of power supplies, degrees of freedom, work envelope, methods of programming, and path motion control. Other points one must consider

have to do with performance measures. The performance measures the text will consider are resolution, accuracy, repeatability, operational speed, and load capacity. From the discussion that follows one can see that these various measures can have an effect on one another.

Resolution. Before trying to differentiate between accuracy and repeatability, one should look at the different variables used to substantiate each. The determination of a robot's accuracy and repeatability is highly dependent on the command resolution and the mechanical inaccuracies of the manipulator itself. Before we discuss accuracy and repeatability, let's take a close look at such concepts as command resolution, mechanical inaccuracies, and spatial resolution.

Resolution is determined by the robot's control system. It deals with the smallest incremental movement the robot is capable of performing. It can also be described as the smallest segment into which the work space can be divided. *Command resolution* can be calculated by dividing the travel distance of each joint by the number of control increments. So if an axis has a travel distance of 36 in. and the controller has a total of 8000 points, then the command resolution, or closest distance between movements, is 0.005 with zero mechanical inaccuracies.

The manipulator employs certain *mechanical members* to position the end effector at the various command positions in the work envelope. Whenever mechanical members are used, whether they be gears, chains, cables, or ball lead screws, certain inaccuracies are present. Gears are prone to have backlash, and chains and cables stretch. When this happens, slippage occurs. Also, overweight payloads can create certain inaccuracies.

Easy positioning of the tool at desired locations during training is important. A robot must be selected that has the capability of positioning the tool within the prescribed location to accomplish the desired task. It is evident that tool positioning is going to vary because of the command resolution and mechanical inaccuracies. The term *spatial resolution* is used to describe the movement of the robot at the tool tip. Spatial resolution takes into account *command resolution* and *mechanical inaccuracy*. Thus, if the previous examples used to calculate command resolution have a mechanical inaccuracy of 0.003 in., then the spatial resolution would be 0.008 in. This figure is derived by adding the command resolution figure of 0.005 in. to the mechanical inaccuracy of 0.003 in.

It is worth noting that in the work envelope spatial resolution varies with tool location. Also, the consistency of spatial resolution throughout the work envelope is affected more by certain robot configurations than by others. The cartesian configuration offers fairly constant spatial resolution throughout its work envelope, whereas robots using rotary joints

can greatly affect spatial resolution unless corrective measures are pro-
vided.

Accuracy.   How does accuracy differ from spatial resolution, given that
both are by-products of command resolution and mechanical inaccur-
acies? Accuracy expresses how close the robot's hand can be pro-
grammed to hit a desired point, whereas command resolution refers to
the small incremental movements between joint positions the robot is
capable of performing. Accuracy performance can be expressed as half
of the spatial resolution. A robot with a spatial resolution of 0.010 in.
would have an accuracy of 0.005 in.

What is the average accuracy employed by robots used in the
United States today? Large robots with payloads of 100 lb or more have
an accuracy of ±0.050 in. Small robots used in such areas as assembly
operations, where payloads are lighter, boast of accuracies of ±0.002
in. Improvement in accuracy will greatly increase in the future.

The accuracy of the robot can be greatly affected by the speed of
movement and weight of the payload. As speed of movement increases,
accuracy decreases. In order for the manipulator to stop at a given lo-
cation, speed has to be reduced to prevent overshooting a position.
However, if the speed is reduced too much, valuable time can be wasted.
Also, the inertia generated by moving a heavy load can affect positioning
accuracy. To overcome the effect of inertia, the speed of movements
may have to be reduced. So in essence there has to be a trade-off con-
cerning speed and accuracy.

Repeatability.   Often the robotic novice confuses accuracy with re-
peatability. Even though repeatability—just like accuracy—is depen-
dent on spatial resolution and mechanical inaccuracy, there is a differ-
ence. The difference has to do with target positioning and repositioning.
While accuracy deals with programming the robot's hand to go where
you want it to go, repeatability expresses how close it will return to
presently taught positions.

Good repeatability is more desirable than accuracy because most
inaccuracies are easier to rectify. This is especially true if the inaccuracies
are consistent for all moves. To illustrate this point, let's use the follow-
ing example. A robot is programmed to move its gripper from point A
to a target point 30 in. away. After the robot has made the move, an
actual measurement is taken and found to be 30.10 in. This represents
an inaccuracy of 0.3 percent greater than the programmed position. If
an inaccuracy of 0.3 percent is consistent for other command move-
ments, then the programmer can compensate for this error. Adjustment
for poor repeatability is more difficult to pull off. In fact, repeatability

may be so poor for a particular robot that a more sophisticated unit may be required. However, if the error of repeatability is rather small, additional tooling or alignment devices can be used to compensate for inadequate positioning.

Repeatability of a robot can change with use. The repeatability for robots that perform the same task day after day is subject to change. The mechanical components in use tend to wear in certain areas, thus increasing mechanical inaccuracies. The increase in mechanical inaccuracies will definitely reduce the repeatability performance of the robot.

Operational Speed. Operational speed of the robot is often referred to as *dynamic performance*. Dynamic performance has to do with how fast the robot can accelerate, decelerate, and stop at a given point. Probably the two most important factors that will influence the work pace of the robots are the accuracy you are trying to achieve and the payload you are moving. However, the robot configuration and the location of the tool in the work envelope cannot be ignored.

A casual glance at the advertising literature of various robot manufacturers will yield many ways to define robot speed. The robot speed may be given for each joint or various groups of joints. The range of velocity may be listed for the robot with no load as well as fully loaded.

We hear a great deal about robots being more productive than humans. Since people consider robots more productive, it is natural to assume that robots work at a faster pace than humans. If you examine most robot installations, you will discover that the speed of the robot's actions are no faster than humans. In fact, many times it is slower. Productivity is gained by the robot working at a constant steady pace. Besides, the robot doesn't take coffee breaks or eat lunch.

So if you are considering a robot for a production application and have based the total cycle time on speed rates furnished by various manufacturers, you may be in for a surprise. You are not interested so much in joint speed as in how fast you can move the end effector through the total cycle and still maintain the desired accuracy and repeatability. Besides, you do not hire individuals by how fast they move their arms or work. You are more concerned with their ability to do a quality job in a reasonable time. So why should robots be any different?

In order to arrive at cycle times that are realistic, you may have to build a prototype layout to determine the time required for various moves. Since a lot of other variables, such as other performance measures, machine cycle times, and conveyor speeds have to be considered, the prototype layout is probably the best solution for deriving realistic cycle times. Besides, the speeds furnished by robot manufacturers are at best just ballpark figures.

Load Capacity.   You can get as many answers concerning the load-handling capacities of robots as you can about speeds. Some manufacturers list *handling capacity by certain situations* such as whether the robot's arm is extended or retracted. Other manufacturers may list load-carrying capacity for the arm as well as for the wrist and end effector. But the two things that greatly affect load-handling capabilities are the type of robot configuration and the placement of the end effector in the work envelope. The load-handling capability for a robot with its boom fully extended is going to be less than when the boom is retracted.

What is the lifting capacity for robots manufactured in the United States? Some models are only capable of lifting 1 lb, such as the Minimover 5 by Microbot. Other robots such as Prab's model FC has a lifting capacity of 2000 lb. In most instances the weight of the gripper or end effector is included in the lifting capacity. If a robot has a lifting capacity of 5 lb and the gripper weighs 2 lb, then the weight of the part cannot exceed 3 lb. Most robot manufacturers will generally list a normal and a maximum load-handling capacity.

What is the average load capacity of robots used in U.S. industry? According to experts in the field, the average weight is estimated to be 20 lb. Approximately 50 percent of robots in industry today handle parts weighing less than 10 lb. The average load-carrying capacity could be even less in the future since smaller robots are being constructed for assembly tasks. It may be of interest to you that 95 percent of all parts used in an automobile weigh less than 5 lb.

In summary, it may be helpful to review the following terms in order to have a better understanding of performance measures.

Spatial Resolution—has to do with the smallest incremental movement of the tool tip. It includes command resolution and mechanical inaccuracies.

Accuracy—used to express the robot's positional ability to hit programmed positions. It includes spatial resolution as well as a defined target point.

Repeatability—used to express the robot's ability to return to a previously taught point over and over again.

Dynamic Performance—used to express the robot's ability to move and stop at a given location with a certain amount of accuracy.

Payload—concerned with the maximum weight or mass of material a robot is capable of handling on a continuous basis. The end effector weight is included in the payload in most cases.

End Effectors

As the industrial robot becomes more prevalent on the factory lines, more dexterous multipurpose end effectors have to be developed. *End effector* is the technical name for the *end-of-arm* tooling on the robot. It is often referred to as the hand or gripper. End effectors can be better defined as devices attached to the wrist of a manipulator for the purpose of grasping, lifting, transporting, maneuvering, or performing operations on a workpiece.

The increased use of robots in such areas as assembly will rely heavily on the development of multipurpose tooling. Two approaches can be used to give the robot flexibility in this area. One approach would be to design multifunction end effectors. The other is to give the robot the capability to change end effectors. Both approaches are used in industry, but today greater emphasis is being placed on quick-change tooling.

The robot's hand is a clumsy imitation of the human hand. As pointed out earlier, the human hand is a very complex multipurpose tool. It not only has the ability to adjust, grasp, pick up, and rotate different-shape objects, but the hand has built-in compliance and sensing capabilities. In order for a person to understand how rudimentary the robot is for assembly, I suggest you reflect on an analogy given to this writer by an automation assembly engineer. This individual indicated that one way to determine if an operation is a candidate for robot assembly is to try to do the assembly behind your back, using only one hand with the fingers taped together. Although this is a crude analogy, there is probably more truth to it than fiction. The development of an end-of-arm tool is not an easy task. Each situation usually requires specially fabricated tooling.

Before we discuss the various types of grippers, or end effectors, let's examine in more detail the movements of the human hand. The two classes of movements are referred to as prehensile and nonprehensile. *Prehensile* movements are employed to grasp or grip an object. The various degrees of freedom, the curled finger, and the opposing thumb provide the hand with its great dexterity. One cannot overemphasize the thumb. Without the thumb humans would be no better off than the other animals. It is the thumb that enables humans to pick up and manipulate very small objects. *Nonprehensile* movements can be described as pushing, poking, punching, and hooking movements.

There are approximately five different prehensions formed by the hand: palmar, cylindrical, spherical, lateral, and oppositional. These types of grips are developed in stages. As the child grows and coordination develops, so do the various grips. The palmar grip can be associated with a baby holding a bottle during feeding. The cylindrical

grip can be used for grasping a cylindrical object such as a baby's rattle or a human finger. With the spherical grip the fingers come more into play. An example of this grip is throwing a baseball. The lateral grip is employed to grasp larger objects. The oppositional grip involves the use of the index finger and thumb. The various types of prehensile grips are shown in Figure 3–5.

There are two types of nonprehensile movements we will consider. They are the hook and the spread. The hook movement can be used to pull drawers open or lift objects with bail-type handles. The spread movement can be used for transporting many objects possessing internal openings. Examples of these movements are shown in Figure 3–6.

From the previous discussion it can be seen that there are various means of grasping, moving, or handling objects. To determine the type or design of end effector necessary to do a job is not as easy as some may think. To arrive at the proper solution, a study must be made concerning the *operation* and the *object* being transported. The operation may be one where the end effector is subject to extreme hot or cold temperatures. It may be an operation where abrasive or corrosive materials are used. These are only a few of the possibilities that may exist. Conditions such as the ones just mentioned may call for special materials to be used as well as for some type of shielding device to protect the robot's arm.

Objects vary in shape, size, and weight. In addition, the object may change in shape, size, and weight during a process. The end effector must have the ability to adjust to such changes. Other object conditions to be considered are fragility, surface finish, and type of material. If an object is made of ferrous material, one that contains iron ore, then a magnetic gripper may be appropriate.

The above-mentioned considerations concerning operation and object characteristics are only a few commonsense items that are quite obvious. A more thorough analysis must be made. Problems associated with inertia, center of mass, gripping force, and friction between the part and the gripper have to be addressed. Other points of concern may be part manipulation for orientation purposes, gripper sensing capabilities, and the need to interact with other pieces of equipment.

Robots pose various options for grasping, handling, and transporting parts. Some common means are mechanical, vacuum, electromagnetic, support, and expandable devices. These different methods will be briefly discussed.

The *mechanical gripper* is the most common means of grasping objects. The gripper employs various mechanical linkages. Activation can be accomplished through gears, cables, chain, or pneumatic actuators. The grippers that employ two stiff fingers are most common in industry today. One or both fingers may move in the clamping operation. In
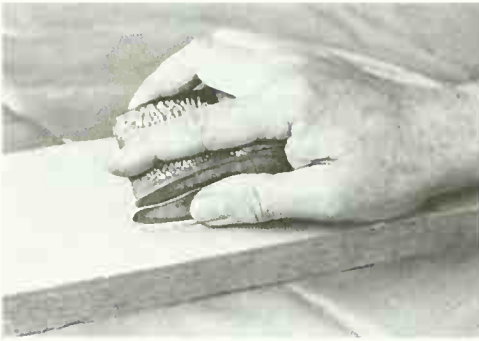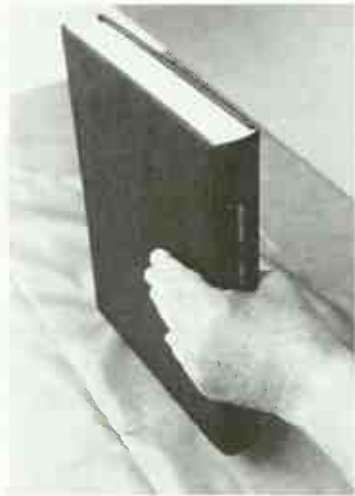
(a)
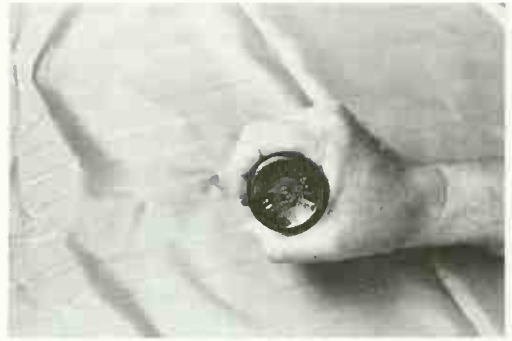
(b)

(c)

(d)

(e)

Figure 3–5.   Five common prehensions of the human hand. (a) Palmer grip. (b) Cylindrical grip. (c) Spherical grip. (d) Lateral grip. (e) Opposing grip.

(a)

(b)

Figure 3–6. Two common types of nonprehensile movements used to move or transport certain objects. (a) Hook movement. (b) Spread movement.

order to accommodate different-shaped objects the fingers can be interchanged. V-shaped fingers are recommended for grasping cylindrical objects. The V shape, with its two-point contact on each finger, insures the centering of the object. Self-aligning padded fingers are used in gripping flat objects. It is possible to have fingers with more than one size or shape cavity in the finger. Multicavity fingers may be required if the object changes shape or size during processing. Figure 3–7 shows some common mechanical grippers that are commercially available today.

The *vacuum gripper* consists of one or more suction cups made of natural or synthetic rubber. The vacuum gripper is extremely lightweight and simple in construction. The number, size, and type of cups depend on the weight, size, shape, and type of material being handled. The cups are considered off-the-shelf items. They can be purchased from various suppliers. A multicup vacuum gripper is shown in Figure 3–8.

Most people probably think of vacuum grippers only being used to handle flat workpieces. But vacuum grippers can be used on curved and contour surfaces as well. Also, vacuum grippers are ideal for handling fragile parts. Vacuum grippers are well suited for handling glass objects. Soft, flexible cups have been developed to handle such fragile things as eggs.

The flexibility of the cup provides the robot with a certain amount of compliance or forgiveness for misalignment. The positioning of a cup at a prescribed point is not as critical as with some other types of grip-
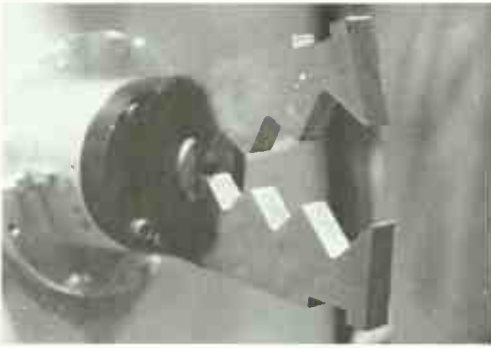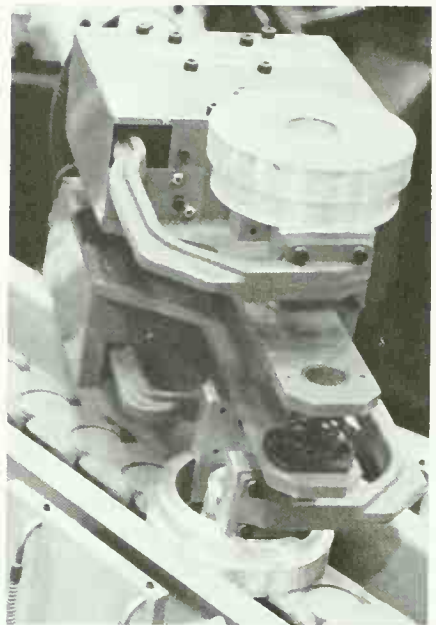
(a)

(b)

(c)

(d)

Figure 3–7. Various types of mechanical grippers. (Photos taken at Robot 7 show in Chicago.) **(a)** V-shaped multicavity gripper. **(b)** Gripper with self-aligning fingers. **(c)** Internal spread gripper. **(d)** Fanuc's double gripper.

pers. To allow for unevenness or distortion in a part's surface, some vacuum cups are spring loaded or mounted on a ball joint.

Magnetic grippers are similar to vacuum grippers. Although the two are compatible in many ways, they do possess distinct differences. Objects possessing flat, smooth, clean surfaces are the easiest to handle.

Figure 3–8. Typical vacuum gripper. (Photo taken at Robot 7 show in Chicago.)

The magnetic grippers can use electromagnets or permanent magnets. The permanent magnets do not require a power source. Permanent magnetic grippers work very well in explosive areas. The part is released from the permanent magnet by force or some type of stripper device. The electromagnet is energized by a dc power source. Release is accomplished by interrupting the power source. To speed up the release time, the direction of current flow is reversed momentarily when the switch to interrupt the circuit is actuated.

There are certain disadvantages associated with magnetic grippers. One disadvantage is that only materials attracted to magnets can be handled with this type of gripper. Objects containing ferrous material or iron ore possess this quality. Operations where parts are being machined can create some problems. The small metal chips or particles will be attracted to the magnet. The attracted particles could get trapped between the magnet and the part. When this occurs, there is a risk of scratching the part with the attracted particles. The attracted particles can also contribute to the problem of misalignment of parts that follow. Another factor that has to be considered is the temperature of the object being handled. After the object reaches a few hundred degrees, the effectiveness of the magnetic force starts to decline.

The magnetic gripper does have certain advantages over the vacuum gripper. The magnetic gripper has a longer life and can handle hotter objects than the vacuum gripper. The magnetic gripper has the capability of lifting heavier objects. Another advantage of magnetic grip-

Figure 3–9.   Magnetic gripper used by Prab Robots Inc.
(Photo taken at Robot 7 show in Chicago.)

pers is rapid gripping capabilities, whereas vacuum grippers require a certain time to build up the absolute pressure. A typical magnetic gripper is shown in Figure 3–9.

Support grippers are usually found on crane-type manipulators. The hook is the most common type of support gripper. Some support grippers are used to support the object from the underside. However, this is a poor means of support because objects have a tendency to topple over or fall with any quick movement.

Expandable grippers are used to clamp workpieces that have geometric variations. The expandable grippers employ a hollow rubber envelope that expands when pressurized. This expandable bladder insures an evenly distributed surface load. The expandable bladder is ideal for handling fragile parts or parts that have a considerable size variation. There are two types of expandable grippers. One type grips the object externally, while the other uses internal gripping for hollow objects.

In summary, there are various methods of holding an object by the end effector. The most common method is through the use of *friction*. That is, the object can be removed with a certain amount of force. If the object is to be held rigid, then a *restrain* type of gripper has to be employed. Magnetic and vacuum grippers can be classified as *attraction*-type grippers. The last and final classification for holding an object is by *support*. As was pointed out earlier, support gripping has limited use.

Until now the discussion has centered around the grasping, handling, and transporting of objects. In addition to handling objects, the robot's arm can be equipped with various types of tool heads for carrying out operations. Spot welder guns, inert arc welders, stud welders, spray guns, drilling heads, milling heads, deburrers, polishers, pneumatic screwdrivers, and nut-runners are some of the common tools being used by robots today. Figure 3–10 shows some of the above-mentioned tools.

As mentioned earlier, one way to increase the uses of robots in various applications is to give them the capabilities to change end effectors. There are two common needs that have to be addressed before this is accomplished industrywide. One is the need to standardize interface adapters. The standardized features of these adapters should provide common mounting and securing systems. All the necessary connectors for the electric, hydraulic, and pneumatic components should be provided with these adapters. Since robots come in different sizes, it is conceivable that different sizes of standard interface adapters will have to be provided. However, these adapters should have the capability of being able to interface with the different robots manufactured.

In addition to standardized interface adapters, rapid tool-changing capabilities are also needed. Quick-changing tool capabilities can enable the robot to handle different-shaped parts and perform wider ranges of assembly tasks and a variety of machining operations with minimum time lost for changing tools. Thus, quick-change tool capabilities can provide the robot with greater flexibility and increase its productivity.

There are certain advantages and disadvantages in comparing the end effector with the human hand. Some noted advantages of the end effector are its ability to withstand higher temperatures, carry heavy loads, work in corrosive areas, and not be concerned with objects possessing sharp edges. Some disadvantages of the end effector are its awkwardness and lack of compliance and sensing capabilities. To overcome these deficiencies, universities and manufacturers are conducting extensive research in these areas.

The end effector should have certain characteristics. It should possess the necessary strength to carry out its tasks and withstand rigorous use. For certain operations a breakaway device should be provided to keep from damaging the robot's arm or wrist if the hand becomes stuck. End effectors that hold objects by friction are generally not bothered by this problem. The object will slip out of the gripper when force is applied. However, the force could cause joint slippage, thus changing position locations.
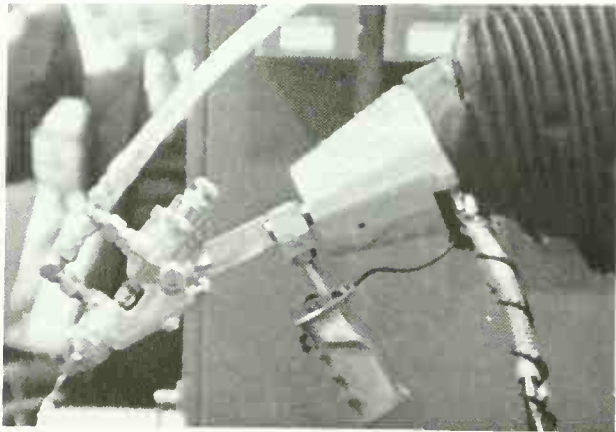
The other characteristics that would be nice for the end effector to possess are compliance and a certain amount of sensing capability. Compliance is concerned with the forgiveness for misalignment of mating

(a)
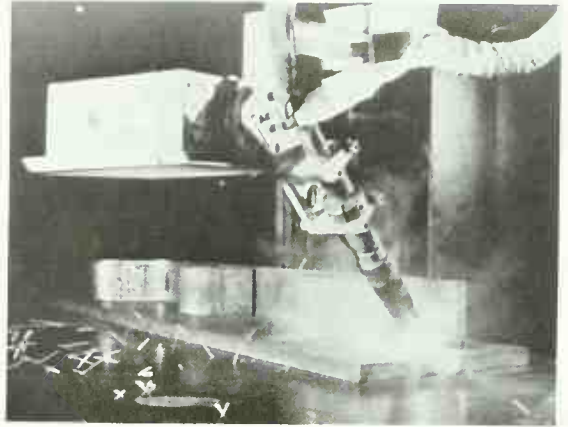
(b)

(c)

Figure 3–10.   Some of the various types of tool heads for the robot. **(a)** Spot welding gun. (Photo taken at Robot 7 show in Chicago.) **(b)** MIG welding head. (*Courtesy of Westinghouse Electric Corp.*) **(c)** Spray gun head. (Photo taken at Robot 7 show in Chicago.)
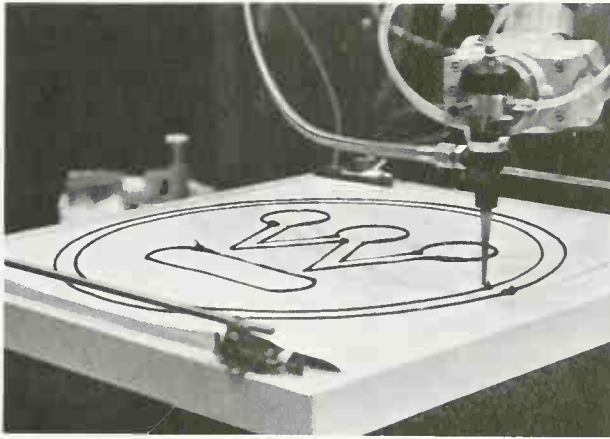
Figure 3–10 *continued.* **(d)** Adhesive applicator head. (Photo taken at Robot 7 show in Chicago.)

parts. In the area of assembly, compliance is a must with close-fitting parts. Compliance enables a part to move slightly, thus avoiding jamming, wedging, and galling of the part.

Some robots have a certain amount of inherent compliance built into them. But for those lacking this capability *remote-center compliance* (RCC) devices are available. The devices fit in the wrist of the robot. Compliance devices have proven successful in the area of assembly. Robots equipped with compliance devices have been able to insert bearings into housing with clearances of only 0.0005 in. One noted compliance device manufacturer is Lord Industrial Products. Figure 3–11 illustrates various compliance devices manufactured by this company.

The need for a sensory system to give the robot the intelligence to perform a variety of tasks is in demand today. To meet the challenge several robot manufacturers have developed end effectors with sensing capabilities. Some end effectors possess tactile sensing capabilities. (IBM's 7565 robot gripper employs tactile sensing; see Figure 3–12.) Proximity and noncontact sensors are being used in several end effectors today. Cincinnati Milacron has developed a seam tracking system for use in arc welding. It is a noncontact sensor that measures the change in the arc's current as the welding torch oscillates across the seam. The robot's computer makes corrections in the robot's position from the signal received from the sensor.

Other types of sensors such as vision and voice are being used today. With the improvement in sensing capabilities, robots will become significantly smarter and be able to handle many of the tasks performed by humans.
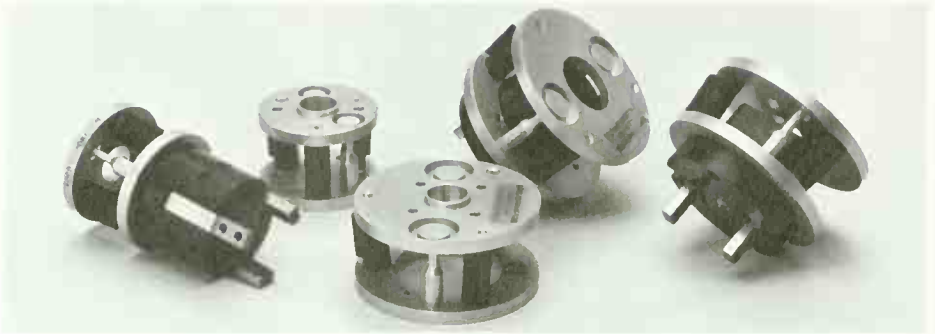
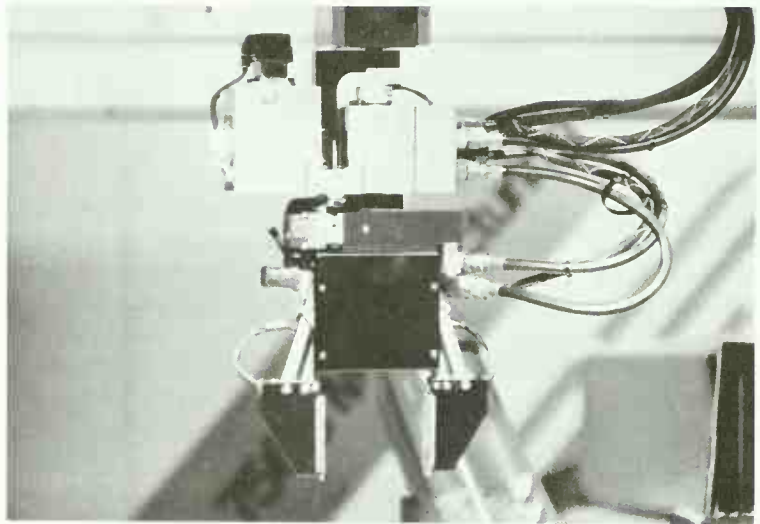**Figure 3–11.**   Lord Corporation's Remote Center Compliance (RCC) Devices. (*Courtesy of Lord Industrial Products.*)

Figure 3–12.   IBM's 7565 end effector. (*Courtesy of International Business Machines Corp.*)

External Sensors

Most experts agree that for the robot to really come of age it must be able to sense, evaluate, make decisions, and interact with its environment. With the perfection of internal and external sensors robots will be able to achieve their full potential. As pointed out earlier, the *internal* sensors are concerned with the internal working of the robot; *external*

sensors are concerned with measuring displacements, forces, or other variables in the robot's environment. The external sensor provides the robot with a higher level of intelligence.

Four common external sensors in use today are vision, tactile, proximity, and voice sensors. Different types of sensors will be discussed in more detail later in the text. However, each will be introduced here to provide some background data.

Vision. More research is probably being conducted on vision sensing than on any other type of sensing. It ranks high on the list of priorities for robot manufacturers. Vision sensing is being used for inspection, identification, and part orientation. There are several problems associated with vision sensing in the areas of orientation and parts assembly. One problem lies in the fact that interpretation and reaction to data is relatively slow. Another problem is that the human eye sees things in three dimensions, whereas most vision systems are only two-dimensional. With two-dimensional systems it is difficult to interpret visual information concerning parts that are stacked in bins. Interpretation is made easier when parts are presented in a single layer. With the increase in the computer software capabilities and better vision systems, these problems will be overcome in the future.

Tactile Sensing. Tactile sensing uses a sensor that makes physical contact with an object. Three types of tactile sensing are touch, force, and torque. *Force sensing* is extremely useful in the area of assembly, especially if clearance is close. Force sensing can prevent part damage, verifies operations, and detects drift. *Touch sensing* can verify if an object is present or not. Touch sensors can be used to control the grip pressure of the end effector. Experimental work in several universities is being conducted using touch sensing for part recognition. *Torque sensing* can be used to indicate tool wear.

Proximity Sensing. Proximity sensing is used to determine if an object is present. Proximity sensors have an advantage over tactile sensing in that physical contact is not required. Measurements can be taken some distance from the object. In addition to using proximity sensors to avoid possible collision, they can be used for the positioning of the end effector to pick up and stack objects.

Voice Sensing. Voice sensing is in its infancy. However, voice recognition can be used to control and program robots. Since this is our natural means of communication, it seems only fitting that this method of sensing will be greatly improved in the future.

REVIEW QUESTIONS

1. Name four methods used to program robots. Briefly define each method and give an application for each.
2. List four proprietary robot programming languages available today.
3. The motion control of the robots have three classifications. List and explain each of these classifications. Which classification is more concerned with controlling the path motion rather than positioning?
4. Define command resolution, spatial resolution, accuracy, repeatability, and dynamic performance.
5. What is the spatial resolution of a robot having a command resolution of 0.006 in. and a mechanical inaccuracy of 0.004 in.?
6. Accuracy and repeatability are often confused. Which appears to be most critical? If a robot has good repeatability and poor accuracy, how may the problem be rectified?
7. What is the maximum weight a robot can handle with a load-carrying capacity of 50 lb when the gripper weighs 8 lb?
8. What effect does weight have on the dynamic performance of a robot?
9. What function does the end effector serve?
10. List four classifications of end effectors and explain each.
11. Differentiate between prehensile and nonprehensile movements. Give examples of each.
12. What are some methods used to handle parts that vary in size?
13. What are four characteristics that an end effector should possess?
14. Give an application where a remote control centering device is recommended. What function does this device serve?
15. Differentiate between external and internal sensors. Which one provides the robot with a higher level of intelligence?
16. List and explain four types of external sensors employed by robots.

FACTORS TO CONSIDER IN THE SELECTION AND IMPLEMENTATION OF ROBOTIC TECHNOLOGY

The first three chapters were concerned mainly with the basic characteristics of robots and the fundamentals of robotics. They were designed to relieve some of the anxiety and misconceptions associated with the subject of robotics. A study of the previous material should have revealed what robots can do *for us* rather than *to us*. The reader should feel more comfortable with the subject and realize that robot technology has a lot to offer our society.

With a better understanding of the subject, where do we go from here? We are aware of the fact that robots have something to offer but how does one implement this technology? A good starting point was best summarized by an acquaintance of the writer. In his presentation concerning the implementation of robots he emphasized the need of knowing where you wanted to go. Once you determine where you want to go, there are systematic approaches that will help you arrive at your destination. This chapter will offer some help along those lines. It will focus on the considerations concerning the application of robotics technology. In addition, the advantages and disadvantages, different industrial applications, robot implementation, justifications, the future of robotics, as well as the social impact of robots will be discussed.

77

Advantages and Disadvantages of Utilizing Robots

Whether one is contemplating the use of a new technology or even the purchase of a new machine, there are certain advantages and disadvantages that have to be considered. The robot is no different. The robot is a machine. We purchase a machine to perform a particular task or tasks, and we should not expect anything else.

Advantages

What are some advantages that can be expected from using robots? Probably the two most outstanding ones are increased productivity and improved quality. Today with greater emphasis on productivity and product quality, robot technology is very attractive. But how are robots more productive than humans?

It must be re-emphasized that robots are no faster than humans. In fact their cycle times are generally slower. Productivity gains are made through the robot's constant work pace. Over an eight-hour shift the robot will usually outperform a human operator—especially if the task is repetitive, boring, heavy, or performed in poor working conditions. Greater gains in productivity can be realized by multishift operations. When identifying possible robot applications, one should definitely consider multishift operations.

How will the use of robots improve product quality? The quality is derived through the accuracy and repeatability performances of the robot. An example of this is in the area of spot welding. A robot may have the capability of placing a weld within 0.050 in. time after time. This would be a hard feat for a human to duplicate, considering the spot-welding gun weighs approximately 100 lb. Even though the gun is counterbalanced, fatigue is certain to take its toll on the operator after several hours of operation. Another way that the product's quality is improved is that robots and other automated equipment demand better-quality components. Human operators may be able to assemble components that are a little out of spec, but trying to do this with a robot or some other piece of automated equipment would be disastrous. The use of automated equipment and robots in all areas of manufacturing demands that parts be within the specifications. Also, parts must have closer tolerances. In addition to closer tolerances, manufacturers are starting to demand 100 percent quality parts from vendors. A screw with the absence of a slot in its head usually presents no problem with a human operator, but if a robot is employed in place of a human, it could cause an operation failure.

The introduction of robots is certain to help reduce personal injuries and increase personal safety. The passage of the Occupational Safety and Health Act (OSHA) of 1970 has provided an incentive for

manufacturers to introduce robots in many operations considered dangerous. Using robots in these areas has eliminated the need for the sophisticated safety equipment required if humans were used.

Another advantage has to do with worker morale. In addition to being moved from the dirty, hostile, and hazardous environment, workers can be placed in more challenging positions. Workers are finding themselves in more responsible positions rather than just being machine operators. Giving the unpleasant jobs and working conditions to the robot and more responsible positions to workers is certain to increase morale.

Manufacturers are concerned with holding down or reducing product costs. Robots can make a contribution in this area. Robots have proven to be a cost reduction method. Some manufacturers have boasted of an increased productivity gain of 400 percent in some areas. Others have boasted of reductions in scrap and rework. General Motors recently reported that four-fifths of their rejects in spray painting came from manually operated areas. In addition to scrap reduction, saving can be realized by reducing material usage. Manufacturers using robots in investment casting and spray painting operations have reduced material requirements substantially. One manufacturer was able to reduce his paint usage by 50 percent. Other savings can be gained through a reduction in energy required to light, heat, cool, or ventilate areas if humans were used in them.

Another advantage that robots offer is flexibility. Most automated equipment is "dedicated"—that is, designed to perform one purpose. Trying to adapt this equipment to other operations many times proved quite costly or almost impossible. Robots possess flexibility. An example of their flexibility is the ability to perform the same task or tasks on different automobile models on the same assembly line. Also, they can be reprogrammed to perform other tasks. Short product life, high variety of parts, and small batch size are projections of the future. Presently 25–30 percent of all manufacturing is performed on lots of 50 or fewer parts. It is projected that this will increase to 75 percent. Robots possess greater flexibility and will serve a key role in flexible manufacturing systems (FMS). In summary, increased productivity, improved quality, reduced product cost, improved worker morale and working conditions, and greater flexibility are some advantages offered by robots. No doubt there are other tangible and intangible advantages that were not mentioned. The ones mentioned were some of the more obvious.

Disadvantages

Robots, like many pieces of equipment, have disadvantages as well as advantages. One of the most obvious disadvantages is that they require capital investment. Robots, just as other pieces of equipment, have to

be economically feasible. If robots cannot be economically justified for operations, they should be avoided. Of course, there are exceptions. Where personal safety is involved, personal safety should come first. Robot justification will be discussed in more detail later in the chapter.

Robots are certain to have an effect on the production line. One robot expert's analogy of a robot's effect on manufacturing is similar to a pinball effect. Parts once presented unoriented have to be properly positioned and oriented. This is due mainly to the rudimentary sensing capabilities of today's robot. However, researchers are working on these problems. Many times work flow has to be changed and additional work space is required. To put it another way, the robot is the easy part. It is all the bells, whistles, and other peripheral tooling and equipment required to interface the robot with the manufacturing line that's the problem. It is not uncommon for the peripheral tooling and equipment to cost more than three times the price of the robot.

Another disadvantage is attitude. If management and workers do not have a positive attitude regarding robots, then installations are certain to fail. In order for any company to change, people must have the desire to innovate. No doubt some workers will feel subjugated or threatened by robot installations. Workers need to be assured that their jobs will be more enriching and challenging because of robots.

Production Applications

Robots, often referred to as the steel-collar worker, have been used in various manufacturing settings. The first robot sold by Unimation was employed in die casting. The robot removed the worker from a very hot and dirty work environment After the robots had proven themselves in this area, they were used in investment casting, forging, and welding. The robots were readily accepted in these areas because they helped to remove the worker from a number of dangerous and demeaning factory jobs. These were jobs no one wanted to do.

The applications mentioned in the previous paragraph are specific applications. However, it is the intention of this text to consider applications in a broader sense. Applications such as pick-and-place, machine loading/unloading, welding, spray painting, machine processing, assembly, and inspection will be discussed.

Pick-and-place, machine loading/unloading, welding, and paint spraying are the most common applications in all industries, whereas welding and paint spraying are most common in the automobile industry. But as robot technology improves, one will see a substantial increase in the assembly areas. This stands to reason since assembly operations can account for over 50 percent of the total labor cost. Evidence of this is seen in General Motors' projected use of robots for 1990.

Of the 14,000 robots GM is planning to have in operation, 5000 will be used in the area of assembly. This represents an increase of over 700 percent.

Pick-and-Place. Pick-and-place applications (the process of picking up parts at one location and moving them to another) are the most common applications found in industry. The palletizing or depalletizing of parts is probably the most common form of pick-and-place, although some pick-and-place operations are used for part orientation.

Robots used for pick-and-place offer certain advantages. Robots have the capability of handling objects that are heavy, light, hot, cold, or fragile. Robots have been very successful in handling fragile parts made of glass or powder metal. In the area of handling heavy objects, the robot can eliminate the need for costly mechanical devices to move heavy objects. Robots used in lightweight pick-and-place applications provide excellent speed while maintaining good accuracy and repeatability. The less sophisticated robots are well suited for pick-and-place applications. Figure 4–1 shows a Mobot robot used to pick-and-place parts baskets in the various bins of a carousel storage rack.

Machine Loading/Unloading. The second largest use of robots in all industries is machine loading/unloading. The robot can be used to load and unload parts at various production operations. Machine loading, die casting, forging, injecting molding, and stamping are some of the common production operations. In Figure 4–2 a Prab robot is used to load and unload a stamping press.

Since most of the operations mentioned are generally considered unpleasant and somewhat dangerous, several benefits can be derived from using robots in these areas. One of the greatest benefits is reduced personal injuries and improved personal safety. Some of the most severe accidents in industry are directly related to press work. By using robots in these areas, there is less chance of personal injuries. In addition to personal injuries, operators in these areas are generally exposed to excessive heat, noise, dirt, and air pollution. Removing operators from these areas will reduce the need for purchasing safety equipment and other costs required to clean up the work environment. Substantial gains can also be expected in productivity and quality if robots are used in these areas. Some of the jobs mentioned have excessive absenteeism. Usually, high absenteeism contributes to low productivity and poor quality.

Welding. The third largest use of robots in industry today is in welding. Some common welding applications are spot, stud, stick, metal–inert gas (MIG), and tungsten–inert gas (TIG). Spot and stud welding
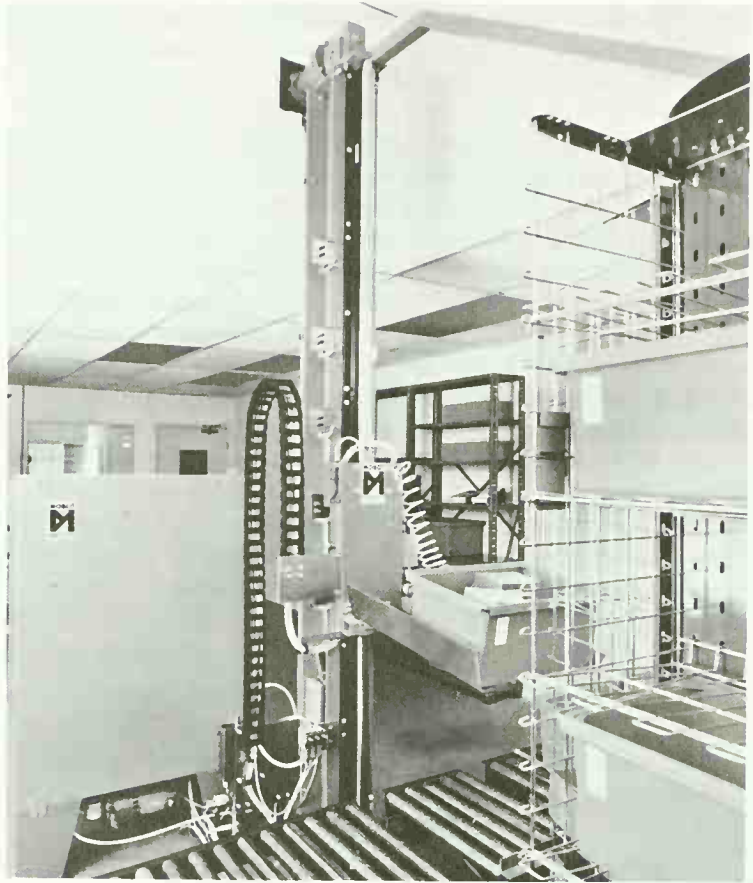
Figure 4–1.   Mobot robot used to pick and place parts totes into various bins of a carousel storage rack. (*Courtesy of Mobot Corp.*)

are classified as resistance welding, whereas stick, MIG, and TIG are arc-welding applications. Of all the welding processes, spot welding is the easiest to perform and the most common. It can be performed on stationary parts or parts moving down a production line.

MIG welding is the most common arc-welding process. This process requires a 100 percent duty cycle arc-welding machine, a wire feeder, a shielding gas, gasflow meter, and a welding gun. The wire is a consumable electrode and the amperage is controlled by the speed of the wire. An inert gas is used to shield the weld from the atmosphere. Figure 4–3 shows the various components of a MIG welding station.

Many of the problems associated with robot MIG welding are mainly due to inconsistent joint fitup. Robot arc welding requires better
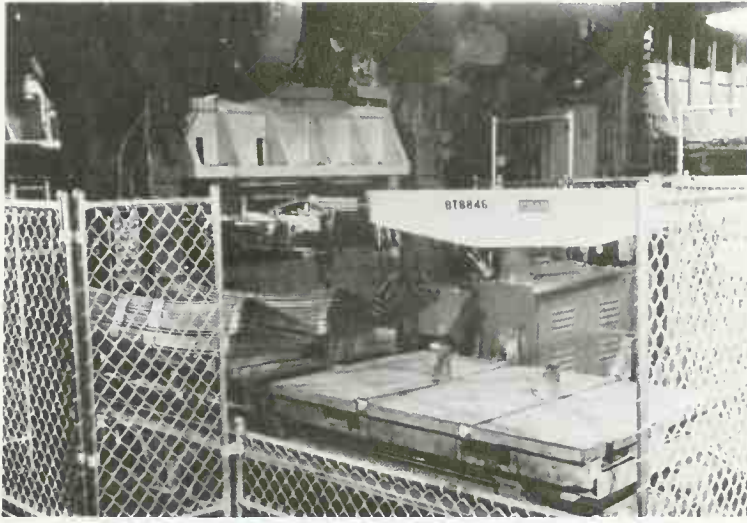
Figure 4–2. Prab robot used to load and unload a stamping press. (*Courtesy of Prab Robots Inc.*)
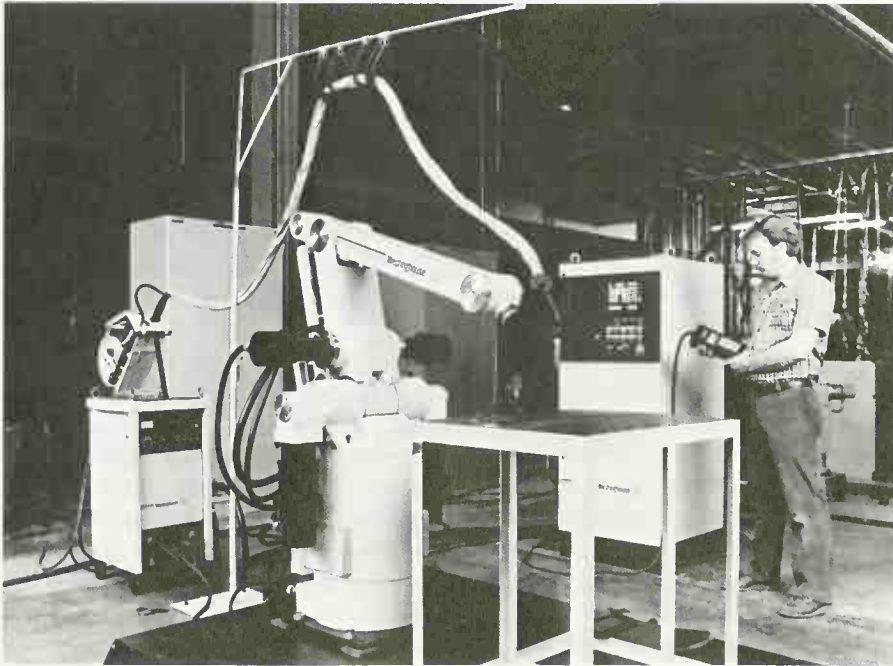
Figure 4–3. Robot M16 welding station. (*Courtesy of Westinghouse Electric Corp.*)

fixturing and better fitting joints than is required by human operators. If joint location or the gap varies, the operator can adjust to these conditions. With the robot it becomes quite difficult to do this. Compensating for gap variation may require a change in the welding dc voltage adjustment, the wire feed rate, travel speed, and weave motion. To compensate for the problem of joint location and gap variation, robot manufacturers have developed sensory control tracking. Cincinnati Milacron's seam tracking system, which was discussed earlier, is one such system.

Robots used in the various welding processes can increase productivity and improve quality. The biggest gain is that the robot removes the worker from an undesirable working environment. Other benefits are reduced training of workers, reduced energy cost, and reduced manpower needs.

Spray Painting.   In spray painting the spray nozzle is mounted on the robot's wrist. Programming is accomplished by having an experienced operator physically move the robot's arm through its cycle. In order to generate a smooth path, an experienced operator should be used. This is important since positioning is recorded on a time sample basis. Since points are sampled at regular intervals, both the intentional and unintentional moves will be recorded. This point-sampling technique, known as continuous-path programming, requires large memory capacity to store the sampled points along the path. For paint spraying, just as with arc welding, path motion is more important than actual point location. In Figure 4–4 the DeVilbiss Trallfa robot is used to spray shutters.

Several benefits can be realized by using robots in spray paint applications. The robot removes the worker from hazardous explosive areas. Since robots cannot see and do not need fresh air to breathe, greater concentration of solvent and reduced lighting present no problem. With the reduction of ventilation, lighting, and heating, energy consumption will be less.

Manufacturing Processes.   Routing, drilling, milling, grinding, polishing, deburring, riveting, and sanding are some of the more prevalent manufacturing processes being performed by robots. Quick-change tooling, better fixturing, increased accuracy and repeatability, and improved sensory and adaptive control will greatly increase the utilization of robots in different manufacturing processes. Robots used in manufacturing processes can increase productivity and improve quality. Also, the robot removes the worker from areas where noise, dust, and poor ventilation may be a problem.

Assembly Operation.   Using a robot to assemble components or products is receiving major attention. Robots, along with other peripheral

Figure 4–4. DeVilbiss/Trallfa TR 3500 finishing robot spray-painting metal shutters. (*Courtesy of DeVilbiss Co.*)

equipment, have been used to assemble such items as calculators, watches, printed circuit boards, automobile alternators, electric motors, and so on. The accomplishments that have been made have only scratched the surface. The potential for robot applications in assembly is tremendous since there is a heavy concentration of labor in that area. In fact, assembly operations may account for 50 percent of the labor cost.

In order for the robot to be more successful in all areas of assembly, robot technology will have to be improved. Better sensory capabilities, improved accuracy and repeatability, improved programming, and better compliance is a must. Although this technology may be required for the more complicated tasks, several of today's assembly tasks can be handled by the less expensive robots.

One may ponder the question of why are assembly operations so difficult and how can these difficulties be removed? A close examination of many products will reveal that they were not designed for automated assembly. In the past development engineers and designers designed
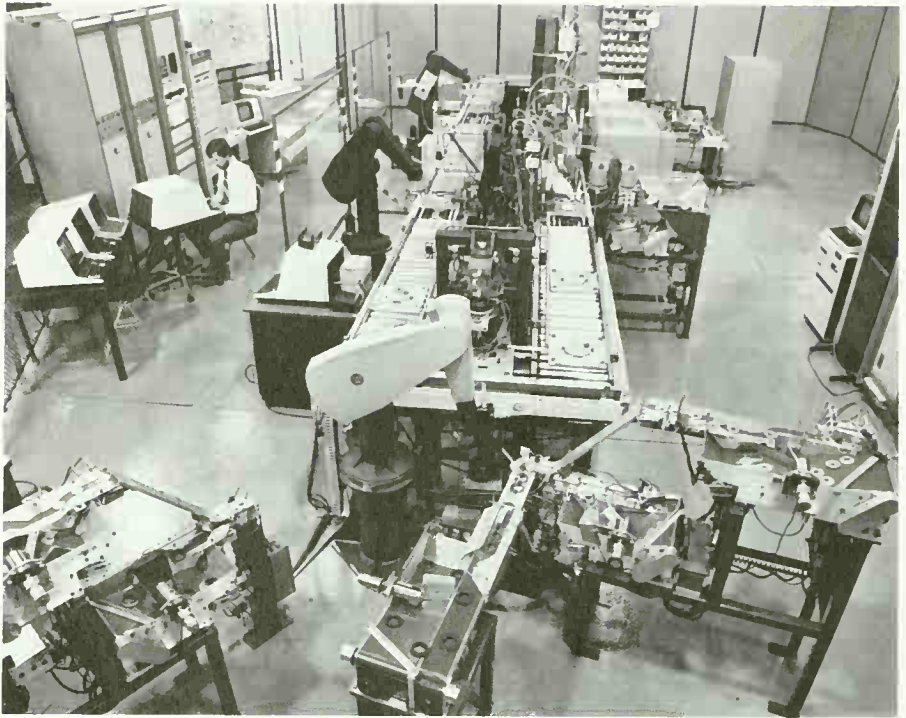
Figure 4–5. Westinghouse's adaptable programmable assembly system (APAS). (*Courtesy of Westinghouse Electric Corp.*)

products without giving much thought to the manufacturing process. The process and the routing of parts was left to the manufacturing engineer. Today that philosophy is changing. Manufacturing engineers are working with the designer in the earlier stages of the design. One of the first questions that the designer must address is how will the product be assembled? If the product is to be assembled by robots or other automated equipment, then the guidelines for automated assembly have to be met. As products are designed for automated assembly, one can expect to find more robots in the area of assembly. Figure 4–5 shows Westinghouse's Adaptable Programmable Assembly System (APAS). APAS is a totally automated batch manufacturing system used in the assembly of seven different end bells for five styles of small electric motors.

Robot assembly relieves the operator from performing boring, repetitive tasks. Product quality is improved because parts have to be of closer tolerance and higher quality to necessitate easier feeding. Increased productivity is achieved by the robot working at a constant pace.
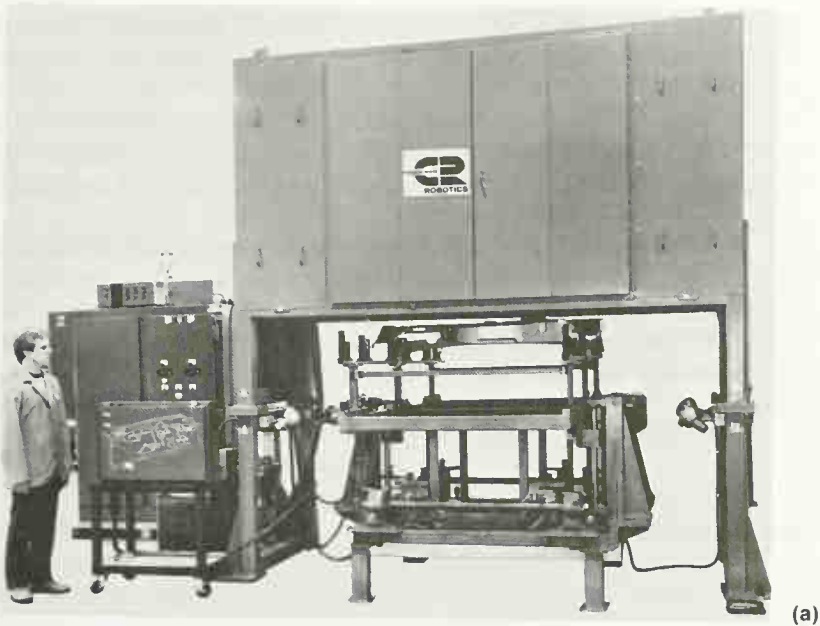
Figure 4–6. (a) Copperweld's Opto-Sense® vision inspection system used to check automotive instrument panels. (b) Automotive instrument panel checked by Copperweld's Opto-Sense®, (*Courtesy of Vuebotics Corporation.*)

Inspection. Like assembly, inspection is a relatively new robot application. Vision sensing used in conjunction with robots has proven quite successful in checking for missing parts or missing features in assembly. Copperweld Robotics, a company recently acquired by Vuebotics Corporation, developed an inspection system for General Motors to inspect and check valve cover pans. The system increased productivity by 400 percent. Figure 4–6 shows Copperweld's Opto-Sense® systsem used to

check for the presence of 50 holes, clinch nuts, and metal splits in automotive instrument panels. The system can make up to 1000 inspections per minute.

Robots can be used for less complicated roles in inspection. They can be used to place parts in inspection gauges or more complex measuring systems. The robot must be capable of performing branching routines to dispose of bad parts.

There are certain benefits derived from using robots in inspection. The robot is well suited for 100 percent inspection. The inspection operation can be incorporated with other operations. The robot reduces the need for many costly inspection fixtures and gauges. Also, the robot has the innate ability to inspect moving parts and obtain consistent results.

Noneconomic Justifications

The decision to use robots is more than a moral issue. Since the cost of robots and their supportive services can be quiet expensive, the decision to employ a robot in a particular situation must prove economically feasible. However, factors such as personal welfare, safety, new technology, and competitive pressures can influence investment decisions. But even when these factors are considered, the decisions still have an economic basis.

Personal Welfare.   Most manufacturers are concerned about the personal welfare of their employees. Many times the robot is used to remove the worker from undesirable situations. Working conditions that are plagued with excessive noise, extreme temperatures, fumes, dust, dirt, and so on, can have a devastating effect on worker performance. Such situations not only contribute to poor worker morale but to higher operating costs as well. Poor working conditions lead to high turnover, absenteeism, low productivity, and poor quality. So in a sense, when robots are employed in such conditions, not only is the worker's welfare a factor but a robot can also prove very cost-effective.

Safety.   Safety, just as personal welfare, has an economic connotation. To bring certain manufacturing processes up to safety standards can be quite expensive. Many times it is considerably cheaper to utilize robots in the various areas than to purchase the sophisticated safety equipment to protect the operator. Using robots in these areas can improve worker morale, increase productivity, and reduce cost.

New Technology.   In the areas of research and development robots are installed for developmental purposes. The motivation behind such installations is to provide knowledge and expertise in the area of robotics that can later be applied to the implementation of robots. Economic returns are received by a reduction in time needed to get robots in production.

Competitive Pressure.   Manufacturers are concerned with lower production cost. However, sometimes it takes pressure from the competition to initiate innovations. If none of my competitors are using robots, then why should I? But just let one competitor start to use robots and gain a price advantage. After this happens, the implementation of robots becomes more attractive. A word of caution: Avoid the me too syndrome. Robot implementations have to be based on firm economic decisions and not on boastful purposes.

With the demand for greater flexibility robots have an advantage over dedicated equipment. As product cycles and market demands change, robots can be reprogrammed for a quick changeover. This will enable the manufacturer to introduce new products or design changes quickly and easily. This flexibility can give manufacturers an advantage over their competition.

Economic Justifications

The consideration to invest in robots may stem from one or more of the previous factors. Even though they are considered noneconomic, one can see that each makes an economic contribution as well. The decision to invest in robots may be based solely on economics. It is usually economics that plays the key role. The discussion concerning economic justification that follows is not intended to make a person an economic specialist. The subject of engineering economics requires more in-depth study than can be provided by this text. The purpose of this section is to provide the reader with a greater awareness of the various factors that must be considered when preparing investment proposals.

Since the industrial robot is considered equipment, it must be handled with the same scrutiny as any other equipment. This scrutiny can be regarded as economic analysis. There are two situations where economic analysis is used. The first situation involves investment in equipment for a new application. This is referred to as *avoidance costs*. The second involves the *replacement* of an existing method and is known as cost saving.

Investment decisions are used to determine the most efficient allocation of capital to investment proposals whose benefits are to be re-

alized in the future. In order to make a decision, there must be at least two alternatives. One alternative may be a present method. The other alternative may be a new proposed method. In simple terms you are asking the question, "Should I continue with the present method or should I make the necessary expenditures?" The investment you are proposing has to be judged on whether or not it provides a return equal to or greater than required by the investor. Most companies establish benchmark criteria for return on investment and payback period that investment proposals must meet. A typical example may be a 25 percent return on investment and a payback period of less than two years.

Tools Used in Making Decisions.   The literature on the economic evaluation of robots focuses mainly on a discussion of payback. Investment decisions based on payback can be misleading. Other factors such as *return on investment* and *discounted cash flows* must be considered as well. Several tools are available for making investment decisions. Tools such as tax credit, depreciation, tax rates, payback, return on investment, present value, net present value, cost of capital, and production information provide insight for making decisions. Since the variables affecting the decision are relatively well known and can be quantified, the decision can be made with a great deal of confidence. Some of these factors will be explored in depth in the following paragraphs.

   Present-value or *discounting procedures* are used to determine the present value of money we expect to receive in the future. Since benefits from an investment are to be derived sometime in the future, it is more equitable to examine them in terms of their present value. By doing this the investment alternatives are placed in a better perspective. The following example will be used to illustrate present-value procedures.

   Suppose someone made you the following proposition. You can receive $1000 today or wait and receive $1450 four years from now. Which one should you choose? You will have to determine if $1450 will be worth more in four years than $1000 is today. We know that inflation reduces the buying power of the dollar each year, so inflation has to be taken into consideration. For the examination we will use an arbitrary inflation rate of 10 percent. The following formula will help you make your decision.

$$P = \frac{F}{(1 + i)^n}$$

$$P = \frac{F}{(1 + i)^n} = \frac{1450}{(1 + 0.10)^4} = \frac{1450}{1.464} = \$990.44$$

where

$$i = \text{expected rate of inflation}$$

$$n = \text{number of years}$$

$$P = \text{present value}$$

$$F = \text{future amount}$$

This shows that at 10 percent inflation $1450 will be worth $990.44 four years from now. This is the discounted value of $1450 after four years at 10 percent. It would be to your advantage to take the $1000 now.

Depreciation is an accounting procedure used to periodically reduce the value of an asset. It is a noncash expense used for tax purposes to show the using up of assets such as machines, buildings, and so on. The value of an asset declines as its useful life is expended.

Several methods are used to depreciate equipment. Some use the *straight-line method,* while others may use a *more accelerated method of depreciation.* The straight-line method reduces the asset's value a uniform annual amount over its estimated useful life. The accelerated method reduces the book value of assets rapidly in the early years and more slowly in the later years. This rapid rate of depreciation provides early tax deductions, which tend to increase profits. However, if a significant tax increase is enacted during the useful life of the machine, it may have a negative effect.

Two methods of depreciation, straight-line and sum-of-years, will be used to illustrate normal and rapid rates of depreciation. They will be applied to the following data.

Cost of machine: $22,000

Estimated salvage value: $2000

Useful life: 5 years

Straight-Line Method

$$\text{Annual depreciation} = \frac{\text{cost} - \text{salvage}}{\text{estimated useful life}}$$

$$= \frac{\$22,000 - 2000}{5} = \$4000$$

Sum-of-Years Method

First, determine amount of depreciation:

$$\text{Cost} - \text{salvage} = \$22,000 - 2000 = \$20,000$$

Second, total the number of years listed:

$$1 + 2 + 3 + 4 + 5 = 15$$

Third, place each of the years represented over the denominator of 15 and list in reverse order:

5/15, 4/15, 3/15, 2/15, 1/15   or   33.3%, 26.7%, 20.0%, 13.3%, 6.7%

Year	Yearly Depreciation Rate (%)	Amount Depreciated	Yearly Depreciation	Stated Value
1	33.3	$20,000	$ 6,660	$13,340
2	26.7	20,000	5,340	8,000
3	20.0	20,000	4,000	4,000
4	13.3	20,000	2,660	1,340
5	6.7	20,000	1,340	0
Total	100.0		$20,000	

Investment tax credits generally are initiated when the economy is slow or sluggish. Investment tax credits enable investors to deduct from their tax liability a percentage of the cost of new machinery and other equipment. The purpose of the tax credit is to encourage companies to invest in new equipment, which in turn should help boost the economy. The latest investment tax credit permits a company to deduct 10 percent up front. The equipment must remain in production for five years in order to receive the full benefit. Anything less than five years is prorated at 2 percent per year. For example, if you purchased a piece of equipment and only kept it in production for three years, you would be required to repay 4 percent of the deduction (2 percent times the number of remaining years).

Taxes play an important role in investment decisions. Taxes are often the deciding factor because a saving in taxes can yield an increase in profits. The tax rate for corporations is based on the amount of income and is subject to change. Presently, the tax rate for the first $25,000 of income is 16 percent. After the income exceeds $100,000 the tax rate increases to approximately 50 percent. The average tax rate for larger corporations is generally figured at 50 percent.

Payback period is expressed in years. The year of payback can be defined as the year when the earnings of the investment alternatives

equal the cost of investment. The whole rationale behind payback is the quicker the investment capital is recovered the sooner it can be reinvested.

Payback period is a popular method used to justify robot installation. However, economic justification based mainly on the payback period method can lead to poor decision making. Since payback does not take into account the time value of money and ignores income beyond the payback period, decisions based solely on payback are inappropriate. In order to choose the most appropriate alternative, you must consider the *return on investment* and *net present value* as well as *payback period*.

Return on investment, or internal rate of return, can be defined as the interest rate which causes the investment to be equal to the discounted future earnings. The interest rate is determined by trial and error. There is no procedure that can be directly used to determine the rate of return. The following formula is used to determine the rate of return for the investment:

$$I = \frac{CF}{(1 + i)^1} + \frac{CF}{(1 + i)^2} + \cdots + \frac{CF}{(1 + i)^n}$$

where

I = investment

CF = cash flow earnings

i = interest rate that makes earnings equal investment

Net present value is the amount by which the present value of projected income exceeds the cost of the investment. It is a method used to evaluate the desirability of an investment. The net present value for each alternative can be computed as follows:

$$NPV = \frac{CF}{(1 + COC)^1} + \cdots + \frac{CF}{(1 + COC)^n} - I$$

where

NPV = net present value

CF = cash flow (earning)

COC = cost of capital (interest rate a firm pays for capital)

I = investment

The payback period, return on investment (ROI), and net present value will be computed for the data concerning three alternatives to determine the best alternative. The cost of capital is to be figured at 20 percent. The mathematical computations will only be shown for alternative 2.

		Data		
		Alternative 1	*Alternative 2*	*Alternative 3*
	Investment	$ 8,000	$10,000	$ 6,000
	Earnings			
	1	1,000	6,000	—
Years	2	5,000	3,000	6,000
	3	8,000	2,000	2,000
	4	2,000	8,500	2,500
	Total	$16,000	$19,500	$10,500

The formula used to determine approximate rate of return for each alternative is

$$I = \frac{CF}{(1 + i)^1} + \cdots + \frac{CF}{(1 + i)^4}$$

Alternative 2:

$$I = \frac{6000}{(1 + 0.32)^1} + \frac{3000}{(1 + 0.32)^2} + \frac{2000}{(1 + 0.32)^3} + \frac{8500}{(1 + 0.32)^4}$$

$$I = 9936$$

The rate of return is approximately 32 percent for alternative 2. Rates of return for alternatives 1 and 3 are approximately 30 and 24 percent, respectively.

The formula used to determine net present values for the alternatives is as follows:

$$NPV = \frac{CF}{(1 + COC)^1} + \cdots + \frac{CF}{(1 + COC)^4} - I$$

For alternative 2

$$NPV = \frac{6000}{(1 + 0.20)^1} + \frac{3000}{(1 + 0.20)^2} + \frac{2000}{(1 + 0.20)^3} + \frac{8500}{(1 + 0.20)^4}$$

$$- \$10,000 = \$12,339 - 10,000 = \$2339$$

In order to determine which alternative is the most appropriate, data concerning return on investment, net present value, and payback have to be analyzed. The following is a summary of those data:

| | *Summary of Data* | | |
	Alternative 1	*Alternative* 2	*Alternative* 3
Investment	$ 8,000	$10,000	$ 6,000
Earnings	$16,000	$19,500	$10,500
Payback	2 yr. 3 mo.	2 yr. 6 mo.	2 yr.
ROI	30%	32%	24%
NPV	$ 1,889	$ 2,339	$ 529

As was pointed out earlier, decisions based on payback can be misleading. According to payback, alternative 3 is the best solution. However, when you consider ROI and NPV, alternative 2 is the best solution.

Economic Analysis. Some of the basic tools that are available for making investment decisions have been discussed. But to really understand their relationships one has to do an economic analysis. An economic analysis is a systematic approach concerned with capital investment. It provides the basis upon which to make a decision. Although there are several methods of economic analysis that can be employed for capital investment, the most common ones used in conjunction with machine purchasing are *return on investment* (ROI), *payback,* and *discounted cash flow.* These terms were briefly discussed in the preceding paragraphs. Now we shall use them to determine the most appropriate alternative for a manufacturing operation.

Although ROI is generally used to compare a prospective machine's saving to its investment, the example that follows will use the ROI to compare a proposed robot's saving to the present method of operation. The savings will be generated through the elimination of two production workers, reduced scrap, tax credit, machine depreciation, and salvage. For the sake of simplicity expenditures concerning building

Figure 4–7

DATA ANALYSIS FOR MANUAL OPERATION

Data Sheet

Costs –
Savings
+

Project Title—Manual Method
Alternative 1

Project Life

Years	0	1	2	3	4	5	Totals
Investments							
1. Equip. and accessories	0						0
Depreciation							
2. Straight-line							
3. Depr. tax reduction (Line 2 × 50%)							
Invest. tax credit (10%)							
Salvage value							
Expenses							
4. Vol. of parts		200.0	220.0	200.0	180.0	150.0	
5. Cost of production		– 40.0	– 44.0	– 40.0	– 36.0	– 30.0	
6. Scrap rate, 4%		– 1.6	– 1.8	– 1.6	– 1.4	– 1.2	
7. Maint. support							
8. Eng. support							
9. Add. tooling							
10. Training costs							
11. Travel							
12. Rearrangements							
Total expense							
13. (5–12)		– 41.6	– 45.8	– 41.6	– 37.4	– 31.2	– 197.6
14. Exp. item tax reduct. (Line 13 × 50%)		20.8	22.9	20.8	18.7	15.6	98.8
15. Total after-tax cash flow	0	– 20.8	– 22.9	– 20.8	– 18.7	– 15.6	– 98.8
16. 20% Present worth factor.	1.00	0.83	0.69	0.58	0.48	0.40	
17. Present worth dollars (Line 16 × 15)	0	– 17.3	– 15.8	– 12.1	– 9.0	– 6.2	– 60.4

occupancy, utilities, property taxes, insurance, and cost of inventory
have been omitted. Only major savings and expenditure line items will
appear on the data sheets (Figures 4–7 and 4–8). The data sheets are a
systematic way of presenting data so it can be easily analyzed. The
following data provide the background information for the analysis.

Figure 4–8

DATA ANALYSIS FOR ROBOT OPERATION

		Data Sheet					Costs − Savings +

Project Title—Robot Machine Loading
    Alternative 2

				Project Life			
Years	0	1	2	3	4	5	Totals
Investments							
1. Equip. and accessories	50.0						
Depreciation							
2. Straight-line		9.0	9.0	9.0	9.0	9.0	−45.0
3. Depr. tax reduction (Line 2 × 50%)		4.5	4.5	4.5	4.5	4.5	22.5
Invest. tax credit (10%)	5.0						
Salvage value	5.0						
Expenses							
4. Vol. of parts		200.0	220.0	200.0	180.0	150.0	
5. Cost of production		0	0	0	0	0	
6. Scrap rate 0%							
7. Maint. support		−3.0	−3.0	−3.0	−3.0	−3.0	
8. Eng. support		−1.0	−1.0	−1.0	−1.0	−1.0	
9. Add. tooling							
10. Training costs	3.0						
11. Travel	1.0						
12. Rearrangements	5.0						
Total expense							
13. (5–12)	−9.0	−4.0	−4.0	−4.0	−4.0	−4.0	−29.0
14. Exp. item tax reduct. (Line 13 × 50%)	4.5	2.0	2.0	2.0	2.0	2.0	14.5
15. Total after-tax cash flow (3–14)	44.5	2.5	2.5	2.5	2.5	2.5	−32.0
16. 20% Present worth factor	1.00	0.83	0.69	0.58	0.48	0.40	
17. Present worth dollars (Line 16 × 15)	44.5	2.1	3.6	1.5	1.2	1.0	−35.1

Milling and Drilling Study

Years of study, 5
Tax rate, 50%
Cost of capital, 20%
Volumes, 200K, 220K, 200K, 180K, and 150K

Alternative 1. Manual Machine Loading/Unloading
    Milling Machine:
        Cycle time, 0.5 min
        Production rate—hour per 100 pcs., 0.833
        Scrap rate, 4% of production
        One operator, $8.00/hr + 50% for general benefits

    Drill Machine:
        Cycle time, 0.5 min
        Production rate—hour per 100 pcs., 0.833
        Scrap rate, 4%
        One operator, $8.00/hr + 50% for general benefits

Alternative 2. Robot Machine Loading/Unloading
    Cost of robot and accessories, 50K
    Production rate—hour per 100 pcs., 0.833
    No scrap
    Rearrangement, $6000
    Engineering support, $1000 per year
    Maintenance support, $3000 per year
    Training cost, $3000
    Travel, $1000
    Salvage, $5000
    Straight-line depreciation
    Tax credit, 10%

The data sheet (Figure 4–7) for the manual method (alternative 1) reveals that no expenditure is made for capital investment. The only expenditure involved was the cost for the production and scrap generated. The cost of production per 100 pieces is calculated by multiplying the labor cost by 0.833. The total labor costs consists of two production workers' pay at $8.00 per hour each plus 50 percent for general benefits (total, $24.00/hr). The cost of production is derived by taking the production quantities times the cost per 100 pieces. Only one shift of operation is required to meet the production forecast.

Cost of production (first year)

$$= (\$24 \times 0.833) \times \frac{200,000}{100} = \$39,984 \quad \text{or 40K}$$

The cost of scrap ($1600) is added to the cost of production. The 50 percent tax rate will reduce the cash flow to $20,800. When the time value of money is applied to each year's cash flow, the total expenditures for alternative 1 are $60,400 (Figure 4–7, line 17).

The analysis sheet (Figure 4–8) for robot machine loading (alternative 2) reveals a total expenditure for the initial investment of $59,000. But the tax credit, salvage value, and tax reduction reduces the total cash flow to $44,500 for the initial investment. The method of straight-line depreciation is used for equipment and accessories. The depreciation yields a tax saving of $4500 per year. Support expenses amount to $4000. After tax deduction the amount of expenses is reduced to $2000 per year. The adjusted cash expenses are subtracted from the saving (line 3 minus line 14). The calculation yields a cash flow savings of $2500 per year. The total time value of expenditures for alternative 2 is $35,100 (line 17).

A summary of the data in Table 4–1 reveals a return on investment (ROI) of 43 percent, a payback of 1.83 years, and a net present value saving of $25,300 for the robot installation. Alternative 2 is the best solution.

Identification, Selection, and Implementation

The question confronting many manufacturers today is whether they should employ robotic technology. The question is similar to questions presented in the previous section: "Do I continue with the present method or would I be better off employing a method that utilizes a robot?" Many times the question concerning the use of robots may be brought to light because of some production problem. To rectify the problem, the use of a robot may be considered. Contrary to what many believe, the robot is not the answer to all problems. There are situations where using a robot is not feasible. Each situation has to be analyzed on its own merit. Many experts have developed procedures to help analyze the various situations. Although each may approach the problem from different angles, each incorporates various sequential steps that are similar in nature.

Before one starts to worry about the selection and implementation of robots, he or she must determine if one can be used. Robot manufacturer representatives may have the answers to questions concerning robot limitations and capabilities, but no one knows the manufacturing processes better than those engaged in them. So the answers to many questions will have to come from within. Persons engaged in the manufacturing process know their problem areas and their requirements. They have to determine if the robot might be a possible solution. The decision should be based on facts and made as quickly as possible. One certain way to have a robot failure is to install a robot on the basis of a hunch or a management edict. Robot installations must be systematically approached.

Table 4–1

ROBOT LOADING VERSUS MANUAL

Compute ROI, payback, and net present value of savings.

$$\text{ROI} = I = \frac{\text{CF}}{(1 + i)^1} \cdots + \frac{\text{CF}}{(1 + i)^5}$$

I = difference in investment
CF = difference in net cash flow (Line 15)
i = solved by trial and error

Line 15	0	1	2	3	4	5	Totals
Alternative 1	0	−20.8	−22.9	−20.8	−18.7	−15.6	−98.8
Alternative 2	−44.5	2.5	2.5	2.5	2.5	−32.0	
	−44.5	23.3	25.4	23.3	21.2	18.1	

Try $i = 40\%$

$$I = \frac{\text{CF}}{(1 + i)^1} + \cdots + \frac{\text{CF}}{(1 + i)^5}$$

$$= \frac{23.3}{(1.40)^1} + \frac{25.4}{(1.40)^2} + \frac{23.3}{(1.40)^3} + \frac{21.2}{(1.40)^4} + \frac{18.1}{(1.40)^5} = 46.97$$

Since 46.97 is greater than the investment, an ROI of 40% is too low.
An i of 44% = 44.08
An i of 43% = 44.78

1. ROI = Approximately 43%

Payback	Years	Cash flow	Cum. total
	1	23.3	23.3
	2	25.4	48.7
	3	23.3	72.0
	4	21.2	93.2
	5	18.1	111.3

2. Payback = 1.83 years
    Net present value of savings can be determined by subtracting the grand totals of present worth dollars (Line 17).
    Line 17

    Alternative 1 = 60.4K
    Alternative 2 = 35.1K

    25.3K

3. Net present value of savings = $25,300.

Preliminary Determination of Robot Feasibility.   The first decision is to determine the feasibility of using robots. To help manufacturers quickly assess situations, William Tanner, president of Tanner Associ-

ates and a noted robotics expert, formulated seven rules of thumb. The rules force manufacturers to look at such things as the complexity of operations, the degree of disorder, cycle times, production volumes, justification, multiuses, and worker attitudes. Tanner suggests that if the rules have a positive implication, then the robot is a right choice for the particular applications in question.

Review of Available Equipment.   If Tanner's rules yield a positive response, the next step is to formulate procedures to explore specific applications in more detail. The first thing one must do is to become familiar with the available equipment. Information pertaining to robot limitation, capabilities, and so on, can be acquired from various sources. One source is the robot manufacturers themselves. There are over 50 U.S. vendors and 300 robot manufacturers worldwide. Other sources are the *Industrial Robot Directory*[1] and *A Survey of Industrial Robots*,[2] which do an outstanding job of presenting information about the robots available today.

As you research this material, you will find that robots vary in capability and level of sophistication. They range from the limited-sequence type to the more complex model controlled by a minicomputer. The task of matching the robot to a particular situation is not an easy job. To help with the task of comparing various robots, a matrix can be constructed for those robots that are of interest to you. The matrix will provide you with a quick means of making a comparison. Also, it will prove most helpful in identifying a particular robot for a given application. The matrix should include such things as the model number, price, number of axes, type of controller, load capacity, work envelope, type of power supply, speed, accuracy, repeatability, methods of programming, and so forth.

Identify Potential Applications.   After you have constructed the matrix, the next step in the sequence would be to identify some potential robot applications. One way to identify possible applications is through a plant survey. Robot manufacturers are more than willing to assist you with this task. If you conduct this task on your own, there are certain manufacturing applications that should attract your attention. If the job is boring, dirty, hot, noisy, or presents a possible health or safety hazard, then the job is a candidate for robot application. Some other considerations are short product life, frequent design changes, family of parts, batch to high production volumes, minimum tool requirements, minimum parts count, and multishift operations. Board applications such as materials handling, component insertion, inspection, and testing are

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[1] Published by Technical Data Base Corp., Conroe, Texas, 1984.

[2] Published by Leading Edge Publishing Inc., Dallas, Texas, 1982.

also likely candidates for robots. Some applications can be identified by reviewing personnel and safety records.

Analysis of Potential Applications.   The plant survey should yield several possible manufacturing applications suited for robots. The next step is to select and construct application profiles of the most promising ones. The study of the various applications will require more work than most people are aware of. It will involve several trips to the production floor as well as talking with the various personnel connected with the operations. The importance of drawing on the expertise of the operators, supervisors, engineers, and other manufacturing personnel cannot be overemphasized. In addition to studying the application, one must be familiar with the previous and subsequent operations because the installation of a robot can have a ripple effect on the whole production line. Parts that are presented without regard to orientation may have to be oriented. Additional material handling and feeding devices may be required. Blueprints, specification sheets, production control, quality, and safety records are other avenues that have to be explored to gain additional information about those applications under investigation.

In addition to understanding the application process, some numerical data has to be generated, for example, numbers and sequence of operations, parts flow, cycle time, product volumes, personnel requirements, product life, tests and quality checks, and other environmental factors. This information will be most helpful in determining if a robot is really capable of handling a job.

Match the Robot to the Application.   The profile of the potential robot applications should yield some favorable robot applications. The problem now is to determine if the job can actually be handled by a robot. A method for using the robot will have to be developed. In reference to earlier comments, be certain to consider the previous operations. You may consider adding, deleting, or combining various steps in the manufacturing process.

The previous review of material concerning available robots should aid in assessing the robot capabilities and matching the appropriate machine to the given application. In addition to the robot, tooling and peripheral equipment needs must be assessed. Don't be surprised if the peripheral equipment costs are higher than the robot. The cost could be three times or more. At this point you also need to arrive at a relevant machine cycle time. If laboratory facilities are available, realistic times, robot performance, and the process sequence can be refined by constructing a prototype of the application under investigation. The information generated will help provide some of the critical data needed to develop the financial proposal.

Develop the Proposal.   The first step in developing a proposal is the preparation of the financial analysis. The financial analysis looks at investment, expense items, savings, and other economic factors to determine the most efficient allocations of capital to the investment proposal. Return on investment, payback periods, and discounted cash flows should be considered for each alternative to determine the most appropriate solution. The financial analysis is used to document the necessary expenditures. Proposals without economic justification are doomed to be rejected.

The proposal is a rather complex document. It generally follows a set sequence and addresses pertinent questions related to the proposed investment. The proposal begins with the statement of the problem. After the problem has been identified, a probable method of solution is formulated. To support the proposed method of solution, a rationale has to be established. The rationale should include the noneconomic factors as well as economic justification. Other areas of the proposal address personnel requirements, required resources, a time schedule, and, last but not least, a budget.

Develop and Refine the Application.   After the proposal has been approved, the details of the actual application have to be worked out. The necessary tooling has to be designed and ordered. The necessary safety devices should be included in this area as well. During this phase the proposed application process has to be debugged and refined before it can be released for implementation. Although this phase of the project has not been expounded on, don't be surprised to find the bulk of the project's time devoted to this area. This is the initial proving ground for the application.

Implementation.   Implementation is involved in getting the site ready for production. The floor space has to be prepared and the various service drops and safety devices installed. This may not seem like much of a problem, but tying a robot into a production line can wreak havoc. You want to create as little confusion as possible. Also, during the implementation, persons involved with the operation of the robot need to be trained. The key to success for any operation is to have personnel who are adequately trained. Without this training the application is certain to be in jeopardy.

Provide Maintenance and Training Programs.   The success of a robot installation often hinges on adequately trained operators and the willingness of the workers to accept the idea. Equally important to the success of the installation is the establishment of a maintenance program. Adequate maintenance personnel need to be trained. It is better to have

too many trained in the area of robotics than to have too few. There is always the problem of covering for people who are sick or on vacation. There is also the problem of turnover. People are transferred, retire, or accept a position with other companies.

Many maintenance workers possess most of the technical skills needed to work on robots. But in addition to these skills, maintenance personnel have to become familiar with the manufacturing process and have a basic understanding of programming. Most robot manufacturers provide schools for training maintenance and other personnel. If only a few people are involved, it would probably be best to receive the training at the robot manufacturer's site. If several need training, it would be better to have the training taught at the installation sites.

Other phases of the maintenance program should include the stocking of adequate spare parts. Down time means loss of production. It is important that the repairs be made quickly. Waiting for a part from the supplier can be embarrassing. The robot manufacturers will supply you with a list of spare parts to stock. As personal experience is gained, a more appropriate list of spare parts for your operation will be generated.

The ongoing success of a maintenance program is to provide up-to-date training. In-service and retraining programs should be a vital part of any manufacturing operation. Not only are these programs needed for the technical personnel, but for all employees in general. Needs for the various groups have to be identified and training programs instituted. Most universities and technical schools are willing to assist in providing this service to industry.

Several factors have been presented that should facilitate the identification, selection, and implementation of robots. This list of factors is not all-inclusive. Only some of the more major considerations have been discussed. These factors were presented in a set sequence where decisions could be made early in the investigation. The very first step in the sequence may rule out robots. The following is a summary of the factors that were discussed.

Determine robot feasibility.
Review available equipment.
Construct a matrix to compare equipment.
Identify potential applications.
Analyze potential applications.
Select the most promising applications.
Match the robot to the application.
Develop the proposal.
Develop and refine the robot application.

Prepare the site and install the robot.

Establish a maintenance program.

Provide in-service and retraining programs for personnel.

The Future of Robotics

Recent sales figures indicate that the United States has done a better job of building robots than they have of selling them. Maybe this is due to the improvement in the economy. Or maybe the would-be purchasers are developing a wait-and-see attitude about this new technology. Robot brain power is expected to increase in the future. The increased memory capacity and improved software should provide a generation of more sophisticated, competent robots. Some may be waiting for these improvements to occur before making any major investments. Some of the other future trends in robotics are discussed below.

Because of the nature of the beast and the stigma attached to the robot, it is only natural for people to compare robot performance with human performance. Researchers and robot manufacturers are busily working on sensory perception for the robot. The use of vision, tactile, and voice communication is expected to increase in the future. Vision and tactile sensing show great promise in the area of part recognition and orientation. The main problem in this early development is that most vision systems are two-dimensional and robot reaction time is too slow. Tactile sensing for use in assembly and part recognition is being conducted by some of the major research institutions. It is evident that better vision and tactile sensing capabilities will have to be developed if the robot is to reach its full potential in the assembly area. Since assembly is expected to be one of the largest users of robots in the future, better sensory perception is certain to come.

Voice communication is in its infancy. Voice communication is being explored for programming and diagnostic purposes. Voice programs are sought as an easy means of programming. Voice programming has proven successful in working with quadriplegics. Some robot experts see robot voice synthesizers used to explain work situations or possible ailments.

The robots of the future are expected to be smaller, more mobile, multiarm machines with increased speed, accuracy, and repeatability. More off-line, easier, and faster means of programming are also expected. Another area where improvements can be expected is end-of-arm tooling. More general-purpose end effectors will be developed. Also, one can expect greater use of quick-change tooling, especially since more robots will be used in assembly.

In the past few years several manufacturing companies have entered the robot business. In 1980 five major robot manufacturers dominated 94 percent of the market. In 1983 their share of the market dropped to approximately 60 percent. Purchasers of robot systems will benefit from more companies entering the market. The robot capabilities will be enhanced and the competition will hold down the prices. However, several of the smaller companies are destined to fall by the wayside.

Social Impact of Robotics

It is evident to all of us that we are living in an era of change, and with change comes resistance. Whether it be a new product, a service, a new discovery, or even a new breakthrough in medicine, people are skeptical of change. This skepticism is usually prompted by our ignorance of the subject. Until we become more knowledgeable of the subject, our attitude is going to be very negative.

If change creates a feeling of uneasiness, what about the rate of change? We are living in a time when the rate of change is at its peak. Technological advances are being heaved upon us at such an alarming pace that it is impossible to keep abreast with some of the more noted developments, let alone the lesser ones. Psychologists tell us that it isn't so much the change that causes the unrest and anxiety but the rate of changes. Never before has the rate of change been so high in our society. Acceptance of this change may be slow, but we will have to adjust. As society becomes more informed of what the robot can do *for us* instead of *to us*, acceptance is inevitable.

Displacement of Workers.   With unemployment at one of its all-time highs, the mere mention of robots creates a lot of unrest. Many people are concerned that the robot will take jobs away from an already depressed job market. True, robots will eliminate jobs. But there are jobs that need eliminating. Jobs that are dirty, dangerous, hazardous, demeaning, and mind-destroying need eliminating.

It is safe to say that the robot will not cause any mass displacement of workers. It is conceivable that 40,000 jobs could be affected by robots in 1990. Although this figure may seem astounding, it only represents approximately 0.05 percent of the blue-collar work force. A more conservative estimate is that 25,000 jobs will be lost to robots.

Past history reveals, except for a few periods, that a major displacement of workers from one occupation is offset by additional jobs developed by the new technology. It is estimated that the robot could eliminate 25,000 jobs, but at the same time it could create 100,000 jobs

needed to build robots and peripheral equipment. Not only would the market be able to absorb those displaced, but it would provide job opportunities for new workers entering the labor force.

Much has been said about the negative effects of robots, but what about the positive aspects? The robot is definitely going to affect the work environment of the worker and the supervisor. Both are going to have more challenging jobs. The supervisor's job is going to consist more in planning activities and less in people supervision. The supervisor will have to be more knowledgeable in the areas of maintenance and administration. The production worker's job will be more enriched. Also, the production worker will have to be more technically competent and more knowledgeable about the whole manufacturing process. One of the most significant changes the worker will notice is that the manufacturing environment will be a cleaner and safer place to work.

Increased Educational Opportunities. Education has been expressed as the foundation on which progress is based. This is especially true of technical progress. Today the demand for educational training in the area of automated manufacturing and robotics is increasing by leaps and bounds. Meeting this demand will require a joint effort on the part of labor, business, government, and educational agencies. No one sector of society can handle the task. The question is pure and simple. Which costs more—education or welfare? It is evident that welfare is a drain on rather than a contributor to society. It can destroy a person's livelihood and kill incentive. Provide someone with the necessary education and technical skills to do a job and she or he will be a contributor to society again.

The education requirement will have two aspects. One will involve the training of those individuals who will be entering the labor force. This means that school curriculums will have to be changed to more closely reflect the needs of business and industry. The other type of training required is retraining programs. The retraining program is a big undertaking because that is where the greatest need will be. Seventy-five percent of the labor force for the year 2000 is in the labor force today. Of the workers displaced by robots, approximately 70 percent will need retraining for new positions. From the percentages just mentioned, one can easily see that retraining is a big job and it is obvious that no one sector of society can handle it. It must be a joint effort.

REVIEW QUESTIONS

1. List four advantages and four disadvantages associated with the utilization of robots.

2. Cite the seven major robot production applications. Which three are the most common? Which one will receive greater attention in the future?

3. The decision to invest in robots can be based on noneconomic as well as economic factors. List and explain four noneconomic factors that can influence the investment decision.

4. Name two situations where economic analysis is used.

5. List and briefly explain the seven tools that are available to assist you in making an economic decision.

6. If someone were to offer you $1500 today or $2000 three years from now, which should you choose? To help you arrive at your decision, compute the present value for $2000 at 10 percent inflation per year.

7. Compute the straight-line depreciation and the sum-of-years depreciation for an investment of $30,000 for a piece of equipment with an estimated salvage value of $5000 and a useful life of five years.

8. Compute the return on investment, payback period, and the net present value of a $20,000 investment with earnings of $9000 for the first year, $5000 for the second year, $7000 for the third year, and $8000 for the fourth year. Cost of capital is 20 percent.

9. Several systematic approaches have been developed for the purpose of identifying, selecting, and implementing robot applications. Summarize the approach presented by this text.

10. List six future trends in robotics.

11. What are two problems associated with vision sensing?

12. People are generally skeptical of change. What argument can you give for their reluctance to accept change?

13. Some experts advocate that robots will eliminate jobs while others say robots will create jobs. What is their reasoning behind these statements?

14. What effect will robots and other automated equipment have on the factory supervisor and the production worker?

15. Why will more emphasis be placed on retraining rather than on training in the future?

AUTOMATED MANUFACTURING SYSTEMS

The advancement of science and technology has brought about some very important changes in the manufacture of industrial products. These include improvements in such areas as product inspection, quality control, detection, automatic processing, sequence timing, and the use of microprocessors.

At one time industrial manufacturing operations were limited to systems and devices that were manually controlled. Gaseous tubes, magnetic contactors, and electrical switchgear served as the primary control devices. Recent developments in solid-state electronics and microminiaturization have brought a number of significant changes to automated manufacturing. Electromechanical, optoelectronic, hydraulic, and pneumatic systems are often combined in the control of a single machine. Industrial robots are examples of machines that use several of these systems to achieve operation.

The Systems Concept

The systems concept is intended to serve as a "big picture" in the study of automated manufacturing systems and robotics. In this approach a system can be divided into a number of subsystems. The role played

by each subsystem will then become more meaningful in the operation of the overall system. Through this approach one should soon be able to see how some of the "pieces" of an automated manufacturing system fit together to form a functional unit.

The word *system* is defined as "an organization of parts that are connected together to form a complete unit." There are a wide variety of different systems used in industry today. An *electrical power system*, for example, is needed to produce electrical energy and distribute it within a system. *Hydraulic and pneumatic systems* are used in industry to accomplish automated operations and to control other system functions. *Optoelectronic systems* are commonly found in inspection applications and for various types of sensors. *Mechanical systems* are needed to hold objects for machining operations and to move them physically on a production line.

Each system has unique features that distinguish it from other systems. There is a common set of parts found in each system. These parts play the same basic role in all systems. The terms *energy source, transmission path, control, load,* and *indicator* are used to describe the various system parts. A block diagram of the basic parts of a system is shown in Figure 5–1.
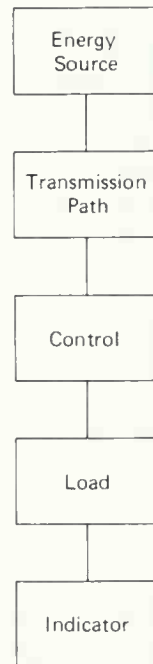
Figure 5–1.   Basic parts of a system.

Each block of a basic system has a specific role to play in the operation of the system. Hundreds of components are sometimes needed to achieve a specific block function. Regardless of the complexity of the system, each block must achieve its function in order for the system to operate properly. Being familiar with these functions and being able to locate them within a complete system is important in understanding the operation of a system.

The *energy source* of a system is responsible for providing energy for the system. These sources include batteries and other dc sources, single-phase ac sources, and three-phase ac sources.

The *transmission path* of a system is simple when compared with other system parts. This part of the system simply provides a path for the transfer of energy. It starts with the energy source and continues through the system to the load device. In some cases this path may be a single feed line, electrical conductor, light beam, or pipe connected between the source and the load. In other systems there may be a supply line between the source and the load and a return line from the load to the source. There may also be a number of alternate or auxiliary paths within a complete system. These paths may be series connected to a number of small load devices or parallel connected to many independent devices.

The *control* section of a system is the most complex part of the entire system. In its simplest form control is achieved when a system is turned on or off. Control of this type can take place anywhere between the source and the load device. Control causes some type of operational change in the system. Changes in electric current, hydraulic pressure, light intensity, and air flow are some of the alterations achieved by automated manufacturing systems.

The *load* of a system refers to a specific part or number of parts designed to produce some form of work. *Work* occurs when energy goes through a transformation or change. Heat, light, chemical action, sound, and mechanical motion are common forms of work produced by a load device. Normally, a very large portion of all energy supplied by the source is consumed by the load device during operation. The load is typically the most prevalent part of the entire system because of its work function.

The *indicator* of a system is designed to display certain operating conditions at various points throughout the system. In some systems the indicator is an optional part, while in others it is an essential part in the operation of the system. In the latter case system operations and adjustments are usually critical and are dependent upon specific indicator readings. Automated manufacturing systems and robotic systems use various types of indicators.

Automated Industrial Systems

The number of automated systems used in industry today is quite diverse. The wide variety of different products that are being manufactured requires many complex machines. Each industry has a number of automated systems and manufacturing processes. Automated industrial systems are ordinarily *synthesized* systems. Electrical, hydraulic, pneumatic, optoelectronic, timing, and digital (numerical) systems are some of the major types of synthesized industrial systems. This classification (synthesized systems) serves as a basis for understanding various automated industrial systems, including robotic systems.

Electromechanical Power Systems

Nearly all of the products manufactured by industries are the end result of the application of some electromechanical power system. Systems of this type are designed to transfer power from one point to another through mechanical motion that can be used to do work. Punch presses that move up and down in a reciprocating motion, rotating machinery, and the movement of robotic systems can all be produced through the use of an electromechanical power system. This type of system is important to modern industry for all types of automated manufacturing.

Mechanical Power Systems

Mechanical power systems also have an energy source, a transmission path, control, a load device, and possibly one or more indicators in order to function properly. These parts are the basic elements of industrial systems. A mechanical power system is a system that produces some form of mechanical motion. As in other systems, the load is responsible for producing this action. An example is movement produced by an industrial robot.

The energy source of a mechanical power system operates by transferring energy of one type into something more useful. The energy source of a mechanical system is often electrical energy.

The transmission path of a mechanical power system could be electrical conductors, belts, rotating shafts, pipes, tubes, or cables. These methods are used to transfer power from the energy source to the remainder of the system. Electrical current flow through conductors is one type of transmission. Hydraulic fluid or air can also be used to transfer mechanical energy through a system. Rotating machines are also used to develop mechanical energy and transfer it to other parts of the system

by belts, chain drives, or shafts. The purpose of the transmission path is to pass mechanical energy from the source to the load.

The control of a mechanical power system is designed to alter the flow of power through the system. Control is accomplished by changes in hydraulic fluid and air flow, pressure, direction, force, and speed. Devices such as pressure regulators, valves, gears, pulleys, couplings, and clutches are commonly used throughout the system. Clutches, gears, brakes, and coupling elements are also used to control such variables as force, speed, and direction.

The load of a mechanical power system is designed to produce some type of motion that can be used to do useful work. Three distinct kinds of motion are important in automated industrial applications: rotary, linear, and reciprocating motion. These motions can be produced by either electrical or fluid power systems. Industrial loads are ordinarily designed for continuous operation for long periods of time. Motors, relays, solenoids, actuators, and cylinders are typical devices used as loads for automated systems and industrial robots.

In a mechanical power system indicators are used to measure a number of physical quantities. These include such variables as pressure, flow rate, speed, direction, distance, force, torque, and electrical quantities. Many of these quantities must be monitored periodically to assure proper system efficiency. A number of indicators are used to test system conditions during maintenance operations. There are several indicators particularly designed to measure the physical changes that take place in mechanical power systems such as industrial robots.

Mechanical Parts of Industrial Robots

The mechanical parts of industrial robots are critical to their operation. There are several unique terms used to define these mechanical parts. One important part is the basic mechanical unit, or manipulator. The *manipulator* of a robot is a mechanism which usually has several moving joints used to grasp and move objects. This mechanism performs the actual work function of the machine.

Another basic mechanical part of an industrial robot is the actuator. An *actuator* is a motor which converts electrical, hydraulic, or pneumatic energy into mechanical energy to cause motion of the robot for performing work. Various types of motors are used as actuators (for example, dc stepping motors).

Other mechanical parts of robots could include *limit switches*, used to break or close electrical circuits, and *relays*, used for electromagnetic control of sequencing operations.
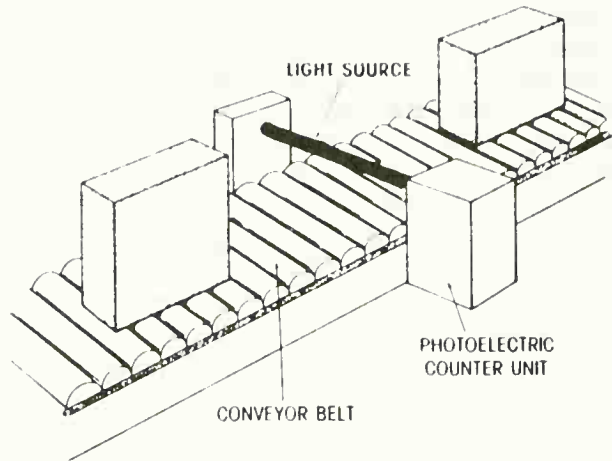
Figure 5–2. Basic parts of a light sensing system.

Sensing Systems

Sensing systems have become one of the fastest growing and most diversified areas in the study of industrial robots. New developments that combine optics, light, electromagnetics, and electronics have revolutionized automated manufacturing. Applications of sensing systems play a very important role in the automation of manufacturing.

Sensing systems respond to various forms of energy. Light energy and electrical energy are widely used with sensing systems. A light source, transmission path, control, and load device are essential parts of the system shown in Figure 5–2. The light source of Figure 5–2 is produced by electrical energy. Light energy is released by the source when it is placed into operation. This energy is then directed away from the source in the form of an intense beam. Incandescent lamps, flames, glow lamps, electric arcs, solid-state light, and laser energy may be used as light sources.

The transmission path of a sensing system is somewhat unique. In Figure 5–2 light energy from the source is emitted into space and travels in electromagnetic waves. Fiber optic rods could also be used as a transmission path in systems that must go around corners or be directed to unusual locations.

Control of a sensing system could be achieved by breaking a light beam between the source and detector. Control is also accomplished by altering the intensity of the light source, its focus, shape, or wavelength. In the detector of the light system control is achieved by altering the

sensitivity of the detector. Adjustments of this type are built into the sensing system so that it can be adapted to specific operating conditions.

The detector of a sensing system is that part designed to respond to some type of energy from the source. Various devices are used to achieve sensing. The output of a detector may be used to control a load device. The load device, as in other systems, produces some form of work. In some sensing systems the load may be controlled directly by light-source energy. In other systems light energy from the source may be detected and amplified to control the load. In some applications the entire detector unit may serve as the load. Sensing systems are now widely used with industrial robots.

Timing Systems

Turning a device on or off at a specific time or in step with an operating sequence is important in automated manufacturing. Systems designed to achieve this type of operation are called *timing systems*. Timing systems presently being used in industry include delay timers, interval timers, and cycle timers. *Delay timing* is designed to precede the energizing of the system load. When a system is placed into operation, there may be a required delay time before the load device actually becomes energized. *Interval timing* occurs after the load has been energized. For example, it may cause the load to remain energized only for a certain period of time. *Cycle timing* systems are typically more complex than delay and interval timers. They are designed to provide some type of energizing action in an operational sequence. This type of timing may include both interval and delay timing.

Timing systems also include such things as thermal devices, motor-driven mechanisms, and mechanical, electrical, electronic, and electro-chemical devices. Many of these systems are energized by electricity. Hydraulic, pneumatic, mechanical, heat, and electrical energy may also be combined to achieve various types of control. Timing systems are used extensively in the control of industrial robots.

Digital Systems

One of the most significant developments that has affected automation is digital systems. Automatic fabrication methods, packaging, and ma-chining operations have been improved through advances in digital sys-tems. In systems that utilize this principle, coded instructions are sup-plied by perforated paper tape, punched cards, magnetic tape, or various physical changes such as pressure, temperature, or electricity. This in-

formation is changed into digital signals and applied to the system. The signals are decoded and directed to specific machines or machine parts, which then perform the necessary operations automatically.

The term *digital*, or *numerical*, *system* implies that numerical signals are used to perform the control function of a system. Most numerical systems in operation today are powered by electricity. This source of energy is used to energize the load device, which performs the work function of the system. The control function of the system must be designed to respond to digital information. Tape machines, card readers, and microcomputers may be used to develop this information. Digital information must be translated into electrical signals. These signals are processed by the logic gates of a computer unit. As an end result, these signals are used to control various machine operations automatically.

The load of a system may be electrical actuating motors or fluid-power cylinders designed to move the physical parts of a machine. When appropriate signals from the control unit are applied to the load, they will move some object to a specific location. Machining operations can be performed according to the information programmed into a digital system. Position location, clamping operations, and material flow can all be controlled by digital systems. Hydraulic, pneumatic, and electrical loads are all easily controlled by programmed information of digital systems. They have revolutionized automated manufacturing methods.

The major emphasis of Chapters 6–9 will be the electrical and mechanical systems used with automated manufacturing systems and industrial robots. The use of electrical and mechanical systems in industrial robot design is a critical element in their operation. The following chapters are organized by using the "systems" format and include coverage of (1) fluid power systems, (2) sensing systems, (3) control systems, and (4) electrical machines and power systems for automated manufacturing and industrial robots.

Control Systems

Various types of control systems are used for the operation of automated manufacturing systems and industrial robots.

The control of industrial robots is accomplished by several electrical and electronic circuits. Some robots have arms controlled by external sensors, while others have mechanical limit switches to act as stops for pick-and-place operations. Servo systems (see Chapter 9) may be controlled by sensors which control the motion of the robot's arm.

Types of Control

Among the simplest control systems are nonservo, or open-loop, systems which use sequencers and mechanical stops to control the end point positions of the robot arm. Robots of this type are sometimes called "pick-and-place" or "fixed-stop" robots. In terms of control, more complex robots are programmable servo-controlled robots. These robots are called "point-to-point" or "continuous-path" types. These robots move in a series of steps from one point to another in a smooth, continuous motion. Programmable robots are typically used for arc-welding and painting operations.

Control Unit Selection

The actual *control unit* of an industrial robot determines its flexibility and efficiency. Some robots have only mechanical stops on each axis, while others have microprocessor or minicomputer control with memory capability to store position and sequence data for controlling motion. Some important factors in the selection of a control unit are (1) speed of operation, (2) repeatability of the control operation, (3) accuracy of positioning, and (4) speed and ease of reprogramming.

Control of Automated Manufacturing

Control of an automated manufacturing system is accomplished by some type of human input or by a physical change that occurs automatically. During production activities at an industry, control systems are continually at work. Control adjustments that alter machine operation must be made periodically. Automatic control is often accomplished by sophisticated and complex control systems. The control functions of automated manufacturing systems range from very simple on-off operations to complex automatic controls that sense a physical change and alter machine operation accordingly.

Basic Control Systems

There is a wide variety of devices used as control systems. The most basic type of control system is referred to as an *open-loop system*. Open-loop systems are used almost exclusively for manual-control operations. There are two variations of the open-loop system. When a system is simply turned off or on, it has *full control*. Switches, circuit breakers, fuses, and relays are used to achieve full control. Full control is designed
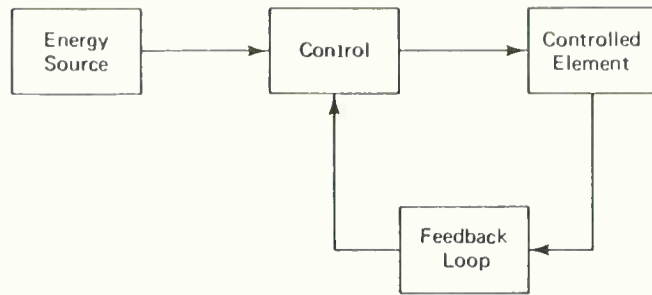
Figure 5–3.   Closed-loop system diagram.

to start or stop the system. In an electrical circuit current stops when the circuit path is opened. Another type of open-loop control is partial control. In an open-loop system partial control alters system operation rather than causing it to start or stop. In an automated manufacturing system resistors, inductors, transformers, capacitors, semiconductor devices, and integrated circuits are commonly used to achieve partial control.

In order to achieve automatic control, there must be some type of interaction between a controlled element and the control section. In a *closed-loop* system this interaction is called *feedback*. Both full and partial control can be achieved through a closed-loop system. Figure 5–3 shows the basic diagram for closed-loop control. The feedback part of this diagram can be activated by electrical, thermal, light, chemical, or mechanical energy.

Figure 5–4 shows the block diagram of a closed-loop system with automatic correction control. In this system energy from a source passes to the control element and to the controlled element. A feedback loop from the controlled element is applied to a *comparator*. The signal is then compared with that of the reference source. A correction signal is developed by the comparator and sent to the control system. This signal is used to alter the system so that it conforms with operational data from the reference source. Systems of this type are designed to maintain the controlled element at a certain operating level regardless of its external variations or disturbances.

Many of the automated manufacturing systems used in industry today are of the closed-loop automatic-control type. Reference signals from a punched tape or cards or microcomputer unit are fed into a comparator along with the feedback signal. An error correction signal is then developed that will alter system control accordingly.

The control of automated manufacturing systems has gone through many changes in recent years. The control function deals with anything
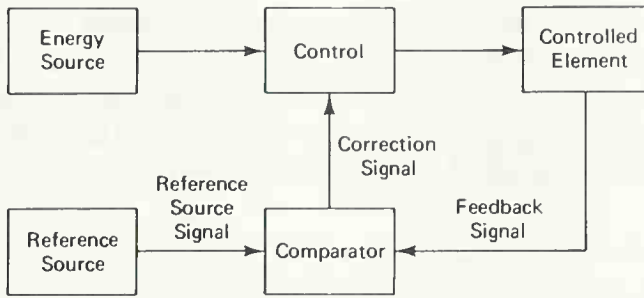
Figure 5–4. Closed-loop automatic control system.

that changes the operation of the system. Control devices are sometimes obvious parts of a system. A number of control devices, however, are not obvious to the observer. These include devices that change the amplitude, frequency, waveshape, time, or phase of signals passing through the system. These functions play a very important role in automated manufacturing systems.

The complexity of a system primarily determines the number of control functions needed to achieve a specific system operation. In many cases there are a number of components used to achieve a similar function in different parts of a system.

REVIEW QUESTIONS

1. Discuss some ways in which manufacturing operations have changed in recent years.
2. What are some systems that must be utilized in the operation of manufacturing equipment?
3. What is a system?
4. What are the basic parts of a system?
5. What is a synthesized system?
6. Why are industrial robots considered to be synthesized systems?
7. How are mechanical power systems used in the operation of industrial robots?
8. How are sensing systems, timing systems, and digital systems used in the operation of industrial robots?
9. How is control of industrial robots accomplished?
10. What is an open-loop system?
11. What is a closed-loop system?

12. What is a point-to-point robot in terms of control?
13. What are some factors in selecting a control unit for a robot?
14. Discuss briefly the control of automated manufacturing systems.
15. What is meant by (a) full control and (b) partial control?
16. What is feedback in a closed-loop system?

Chapter 6

SENSING SYSTEMS

The control of automated manufacturing systems and industrial robots is, in many cases, dependent upon various types of sensing systems. Many systems perform their basic operation because of inputs from some type of sensing system. A sensing system usually converts one type of energy, such as light, heat, sound, electromagnetic, or mechanical, into electrical energy. The electrical energy supplied to the manufacturing system by means of a sensor input may then affect the operation of the machine. Some modification in machine operation is caused by sensing system inputs.

Sensor Control of Robotic Systems

Sensor control of robotic systems allows the robot to determine its own action based upon its sensing capability. Simple sensor control is accomplished by contact switches which stop the arm movement or open and close grippers. More complex robotic systems use touch, force, or torque sensing to affect operation of the system. Touch sensing, for example, may be used to determine position and identify parts. Proximity, range, and vision sensing systems may also be rather complex in nature.

The use of sensors gives industrial robots a new dimension of usefulness. Sensors provide a higher level of intelligence by allowing a greater degree of decision-making capability. The following sections discuss some of the types of sensors used with robotic systems in industry.

Proximity Sensors

Proximity sensors are electronic devices that sense the closeness of some object. Most proximity sensors detect the absence or presence of an object within a sensing region. Others provide feedback relative to the distance between the sensor and an object (usually an end effector).

Optical proximity sensors measure the amount of light reflected from an object. They may use either visible or infrared light. Most optical sensors require a light source. Incandescent lights can be used; however, light-emitting diodes (LEDs) are generally preferred since they have greater reliability and are not sensitive to shock and vibration.

LEDs or solid-state lamps are small, lightweight optoelectronic devices. They are easily used with digital and other miniaturized systems. The semiconductors used in LED fabrication have the unique property of producing photoemission when an electrical potential is applied to the LED. Thus, electrical energy causes the radiation of visible light energy. The response of LEDs varies according to the type of semiconductor materials used in their design. LEDs are made to produce different colors of light. The wavelength of radiated energy from an LED is beyond the visible range.

Eddy current proximity sensors are magnetically operated devices that produce a magnetic field in the small space of a detector unit, which may be mounted in a probe assembly. The magnetic field produced by this type of sensor induces eddy currents into any conductive material that is near the probe assembly. A pick-up coil may be used to sense any change in magnetic field intensity to detect the presence of an object at a close distance.

Reed Switches

Another magnetic sensor that may be used is a reed switch. Reed switches are unique devices that respond to a controlled magnetic field. They are designed to make and break contact when exposed to either a permanent magnetic field or to an electromagnetic field.

The contacts of a reed switch are housed inside a hermetically sealed glass tube. When actuated, contact sparks are isolated from the outside environment. Construction of this type lends itself well to ex-

plosion-proof applications. Switch contacts are also isolated from outside dust and corrosion, which means improved operating life expectancy.

Physically, a dry reed switch contains two flat metal strips, or "reeds," housed in a hollow glass tube filled with an inert gas. When the reeds are exposed to a magnetic field, they are forced together, thus making or breaking contact depending on their design. The normally closed switch breaks contact when influenced by a field. Normally, open contacts, by comparison, are forced closed when influenced by a magnetic field.

Touch-sensitive proximity detectors operate on capacitance developed by a large conductive object (such as the human body). This capacitance changes the resonant frequency of a tuned electronic circuit and causes circuit conditions to change. A conductive plate or rod can be used to sense contact with an object.

Acoustical proximity detectors have a cylindrical, open-ended resonant cavity. Standing waves are developed inside the cavity and are modified by the presence of an object. A microphone may be used to detect a change in sound pressure to measure the distance of an object from the detector.

Range Sensors

Range sensors are used to determine the precise distance from a sensor to an object. Such devices would be useful for locating objects near a work station or for controlling a manipulator. A range sensing system, which can be adapted for use with robotic systems, is called laser *interfero-metric gauges*. They are very expensive and are sensitive to humidity, temperature, and vibration. Another range sensing system is a television camera, which operates on the *sonar* principle.

Tactile Sensors

Tactile sensors indicate the presence of an object when it actually touches the sensor. Two types of tactile sensors are touch sensors and stress sensors. *Touch sensors* respond to touch only, while *stress sensors* produce a feedback signal that indicates the magnitude of the contact made between the object and the sensor.

A simple type of touch sensor is a *microswitch* mounted on the work space. *Limit switches* are also used to respond to contact with an object. Devices called *strain gauges* are often used as stress sensors.

Visual Sensors

Visual sensors can be used to recognize objects or to measure specific characteristics of objects. Camera-equipped computer systems are used to recognize objects. This type of recognition system is used to identify a part by taking a picture through a television camera and distinguishing that part from any other part that might appear before the camera. An object may be identified by its shape, perimeter, or area. These features allow the part to be recognized regardless of its orientation to the camera.

Computer vision sensing systems may be used to sense spatial relationships between a camera, an end effector, and a workpiece. This procedure can be used to provide *depth* information. Two processes now in use for depth measurement with a camera are called stadimetry and triangulation. *Stadimetry* is used to determine the distance to an object based on the apparent size of a camera image. The *triangulation* method is based on measuring angles and size of a base line of a triangle at the location of the object whose dimensions are to be determined.

Another example of proximity sensing is position detection by solid-state TV cameras. A camera can be placed in a robot's end effector to provide visual feedback to guide the effector to a specific location. This process, which may be readily used for material movement, is referred to as *visual servoing*. Servo movement is accomplished by means of visual sensing. This method may be used with either stationary or moving objects.

Light Sensors

One major type of sensing system includes devices that are sensitive to changes in light energy. Light sensing systems operate primarily due to various optoelectronic devices used as sensors.

Control circuitry for automated manufacturing now utilizes optoelectronic devices for many applications. The term *optoelectronic* refers to the combination of light optics and electronics. Thus, electronic light-sensitive devices are called optoelectronic devices. These devices may be used to sense the presence of light, serve as routing systems for assembly line processes, transmit electronic signals with no electrical connection to a circuit, or numerous other applications. These systems, along with some closely related systems such as lasers and X-rays, are becoming increasingly important in control circuits.

Optoelectronic devices are light-sensitive devices that rely on the characteristics of light in order to function. Light is a visible form of radiation that is actually a narrow band of frequencies along the vast electromagnetic spectrum. The electromagnetic spectrum, shown in Fig-

WAVELENGTH
(NANOMETERS)

WAVELENGTH
(MICROMETERS)
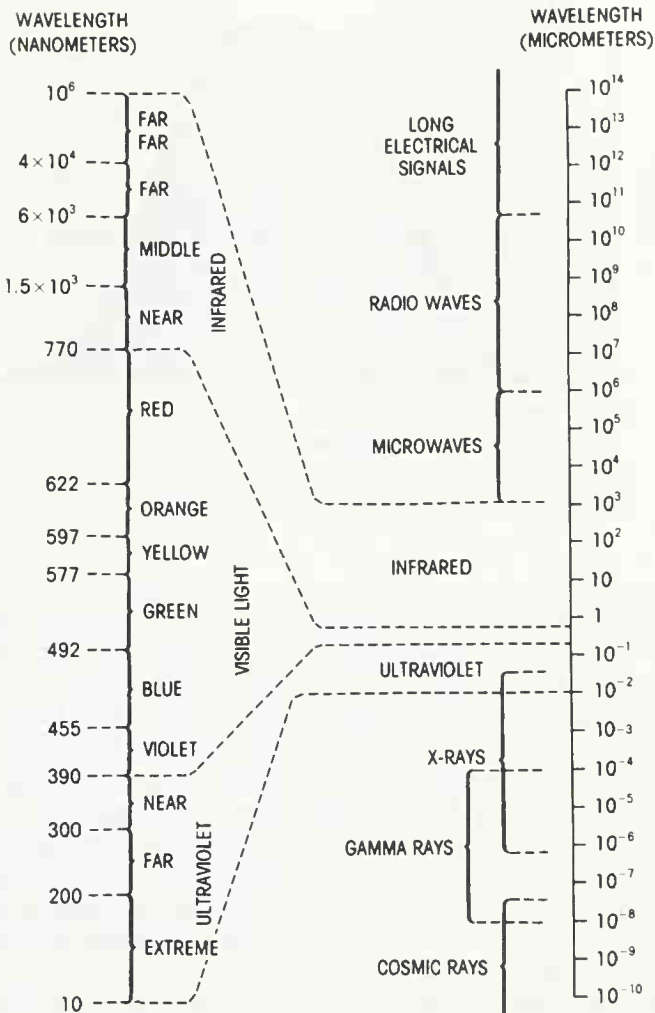
Figure 6–1. Electromagnetic spectrum.

ure 6–1, includes bands of frequencies for radio, television, radar, infrared radiation, visible light, ultraviolet light, X-rays, gamma rays, and various other frequencies. The different types of radiation, such as light, heat, radio waves, and X-rays, differ only with respect to their frequencies or wavelengths.

The human eye responds to electromagnetic waves in the visible light band of frequencies. Each color of light has a different frequency or wavelength. In order of increasing frequency, or decreasing wavelengths, colors range as follows: red, orange, yellow, green, blue, and
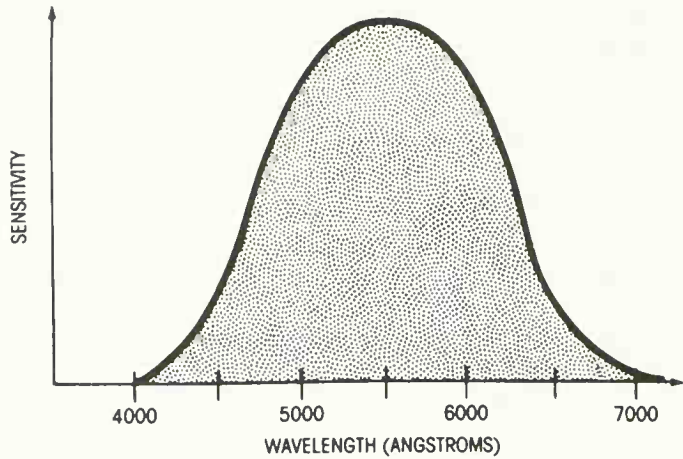
Figure 6–2.   Response of the human eye to visible light.

violet. The wavelengths of visible light are in the 400-nm (violet) to 700-nm (red) range. A micrometer (μm) is one millionth of a meter; therefore, a nanometer (nm) is 1×10^{-3} μm. Angstrom units (Å) are also used for light measurement. An angstrom unit is one-tenth of a nanometer. Thus, visible light ranges from 4000 to 7000 Å. The response of the human eye to visible light exhibits a frequency-selective characteristic (see, e.g., Figure 6–2). The greatest sensitivity is near 5500 Å, and the poorest sensitivity is around 4000 Å on the lower wavelengths and 7000 Å on the higher wavelengths. The human eye perceives various degrees of brightness because of its response to the wavelengths of light. The normal human eye cannot see a wavelength of less than 4000 Å or more than 7000 Å (400–700 nm).

Optoelectronic (photoelectric) devices have typically been considered as falling into three categories: (1) photoemissive, (2) photoconductive, and (3) photovoltaic. *Photoemissive devices* emit electrons in the presence of light. Phototubes are a type of photoemissive device. *Photoconductive devices* are designed so that their electrical resistance will decrease when light becomes more intense and increase when light intensity decreases. Photoconductive devices are also called photoresistive. *Photovoltaic devices* convert light energy into electrical energy. When a photovoltaic device is illuminated, an electrical voltage is created by the device. Most optoelectronic devices fit into one of these categories. However, there is a diversity of new semiconductor optoelectronic devices used in industry today. Several related systems also have applications in automated manufacturing.
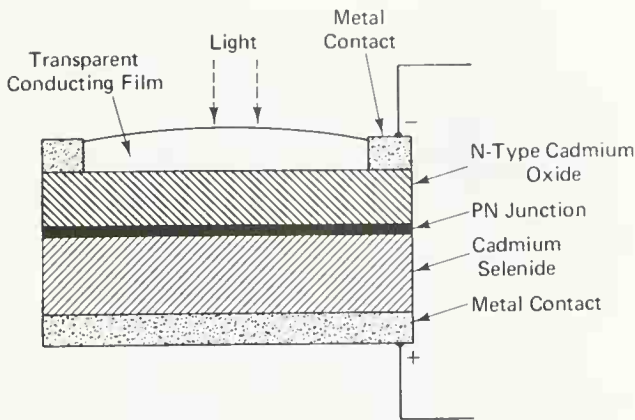
Figure 6-3. Construction of selenium photovoltaic cell.

Photovoltaic cells, commonly called *solar cells*, are used to convert light energy into electrical energy. The electrical output of the solar cell is proportional to the amount of light falling onto its surface. The construction of a photovoltaic cell is shown in Figure 6–3. This selenium cell has a layer of selenium deposited on a metal base, then a layer of cadmium. In the fabrication, one layer of cadmium selenide and another layer of cadmium oxide is produced. A transparent conductive film is placed over the cadmium oxide, and a section of conductive alloy is then placed on the film. The external leads are connected to the conductive material around the cadmium oxide layer and the metal base. When light strikes the cadmium oxide layer, electrons are emitted and move toward an external load circuit. A deficiency of electrons is now created in this region, which is filled by electrons from the selenium material. Now electrons are removed from the metal base into the selenium. Thus, light energy causes a voltage to be developed between the two external terminals of the device.

Selenium cells have a low efficiency of converting light energy to electrical energy; therefore, silicon cells are now more frequently used since silicon cells have higher efficiencies. A silicon photovoltaic cell is shown in Figure 6–4. When light strikes the cell, a voltage is developed across the external leads. The more intense the light, the greater the voltage across the cell.

Photovoltaic cells are used for a variety of applications. Although their electrical output is low, they may be used with amplifying devices to develop an output that will drive load devices of automated manufacturing systems.
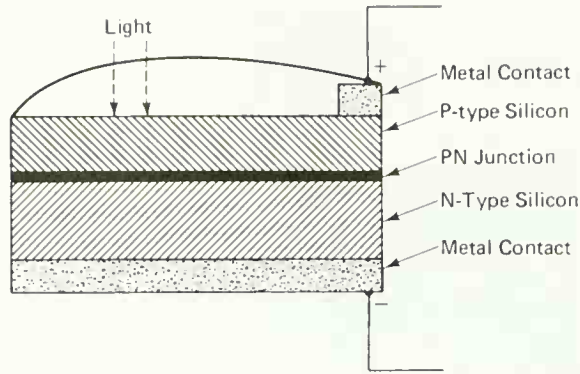
Figure 6-4.   Construction of silicon photovoltaic cell.

Photoconductive devices, such as the one shown in Figure 6–5, are designed to vary in their electrical conductivity when variations of light energy occur. Such devices are also called *photoresistive*, since their resistance varies in inverse proportion to their conductivity. The cadmium sulfide (CdS) cell shown in Figure 6–6 is a common type of photoconductive cell. When exposed to varying intensities of visible light, the cadmium sulfide cell will change resistance. An increase in light energy falling onto its surface will increase the cell's conductivity. The cell is highly sensitive to variations of light intensity. These devices are control systems to provide variable sensing due to light level.

Infrared Sensors

Another type of device that responds to radiant energy is referred to as an *infrared detector*. These devices respond to radiation in the infrared region of the electromagnetic spectrum (see Figure 6–1). Industrial applications of infrared devices now include heat-sensitive control systems, optical pyrometers, and infrared spectroscopy for gas analysis.

An important principle of infrared detection is that all objects emit infrared radiation. Infrared camera systems can produce images in darkness by detecting infrared thermal radiation. Infrared detectors may be used to detect any heated object with no light source used.

Ultraviolet Sensors

Sensors are also designed to respond to electromagnetic radiation in the ultraviolet range (see Figure 6–1). Some design problems have been encountered with ultraviolet sensors; therefore, they are not used as often as detectors for the visible light and infrared energy.
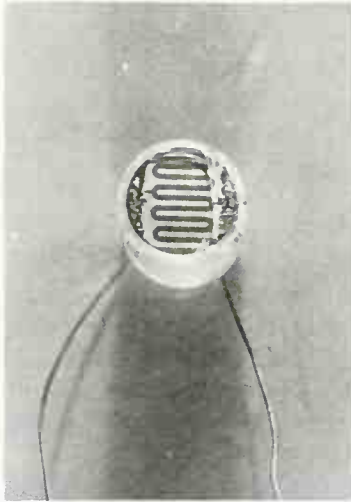
Figure 6–5. Photoconductive sensor.

(a)

(b)
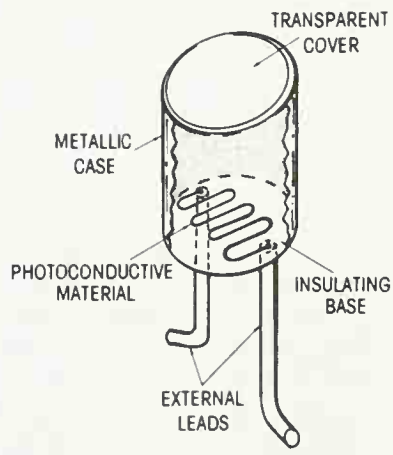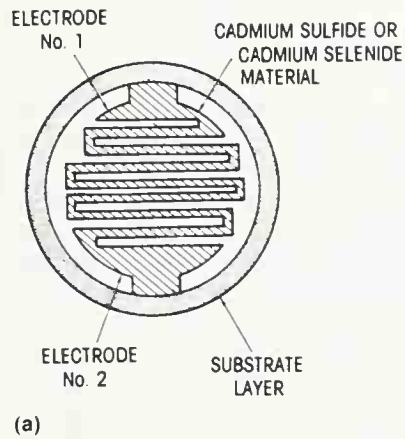
Figure 6–6. Cadmium sulfide photoconductive cell. (a) Top view. (b) Cutaway view.
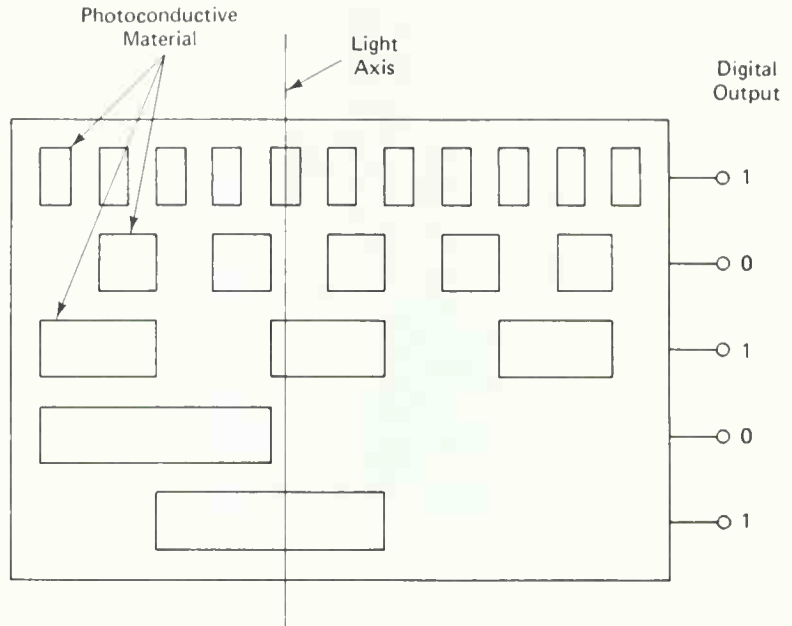
Figure 6–7.   Optoelectronic digital readout position indicator.

Optoelectronic Position Sensors

Various types of optoelectronic devices have been designed to sense the position of a light beam. These devices ordinarily produce an electrical output based upon the position of a light beam. These devices may be used with digital control systems to produce electrical outputs, as shown in Figure 6–7. The electrical signal output is based on the patterns of the photoconductive material onto which the light line is focused and may be used for automated manufacturing operations.

Fiber Optic Sensors

The principle of fiber optics, illustrated in Figure 6–8, utilizes optical fibers made of glass or plastic to transmit light from one point to another. Light may be transmitted in very unconventional ways, such as around corners, in limited space, or over long distances, by using the fiber optics principle. The light will transmit through the fiber optic material regardless of how it is bent or shaped. The core of the fiber optic material is designed to be reflective to the light passing through it. Advances in fiber optic design have made possible low-loss fiber lengths which are used for numerous applications.
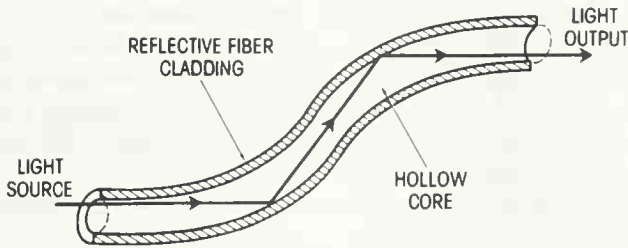
Figure 6–8. Cutaway view of an optical fiber.
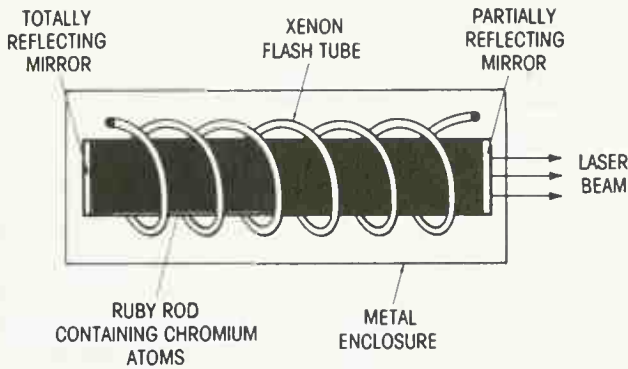
Figure 6–9. Simplified diagram of a ruby laser.

Laser Sensors

The development of the laser has had a significant impact on industrial control systems and promises many more potential uses in the future. Lasers are presently used in welding processes and industrial measurement. The major advantage of lasers is that their radiation can travel long distances with relatively little divergence at one specific wavelength. This is in contrast to other light sources, which have poorer directional and wideband wavelength characteristics.

The term *laser* means *light amplification by stimulated emission of radiation*. This principle may be illustrated by referring to the simplified diagram of a ruby laser shown in Figure 6–9. When the xenon flash tube is activated, the chromium atoms contained in the ruby rod absorb photons of light due to the xenon flash tube action. The chromium atoms then emit photons of energy. Many of these photons of light energy reflect back and forth through the ruby rod, being reflected by the mirrors on each end. The concentration of photon energy within the ruby

causes what we refer to as *stimulated emission*. The chromium atoms emit photons of light energy due to the initial action of the xenon flash tube. These atoms emit photons in the same direction and phase as the initiating photons from the xenon flash tube. The cumulative action which takes place causes a laser beam to be emitted through the partially reflecting mirror at one end of the ruby rod. The laser beam is very concentrated and penetrates the mirror due to stimulated emission or light amplification.

Another laser light source used with sensing and control systems is the gas laser. A popular type of gas laser is the helium-neon laser; however, many other types are available which use basically the same operational principle. The helium-neon gas laser is shown in Figure 6–10. A high dc potential is applied to the plasma tube by means of a voltage multiplier circuit and a pulse transformer. The filament contained within the plasma tube is heated by a 6.3-V ac potential. This filament, when heated, is a source of electrons that are accelerated by the high dc potential. As the electrons from the filament are accelerated toward the high dc potential, they strike helium-neon gas atoms and cause them to ionize. The ionized gas causes the emission of light similar to the action of a fluorescent light. The light beams reflect from the flat, fully reflective mirror shown at the top of Figure 6–10. The plasma tube is cut at a precise angle to cause a controlled reflective angle through the capillary tube. The light is reflected back toward the partially reflective spherical mirror where it is concentrated, due to the action of this mirror, into a laser beam which is emitted through the mirror. A beam reflects back and forth between the mirrors several times before it is emitted. Again, the emitted light beam is produced by light amplification or stimulated emission.

It is also possible to generate laser beams by utilizing the principles of semiconductors. These lasers have a resonant cavity similar to other lasers except that it is formed on a chip of semiconductor material. *Semiconductor injection lasers*, such as the example shown in Figure 6–11, are very efficient and small in physical size compared to other lasers. The end faces of a gallium arsenide chip, shown in Figure 6–11, must be carefully fabricated so that they are parallel and flat. Since gallium arsenide is a reflective material, no mirrors are needed to produce reflection. This is a distinct advantage of the semiconductor injection laser.

As current flows through the semiconductor laser chip, light is emitted from the material. Stimulated emission of light energy occurs when atoms collide near the *pn* junction of the material and cause the release of additional photons of energy. Due to the reflective properties of gallium arsenide, a wave of photons is developed between the flat, reflective surfaces of the material. The back-and-forth movement of this wave of photons creates the resonant action required for the stimulated emission of radiation.
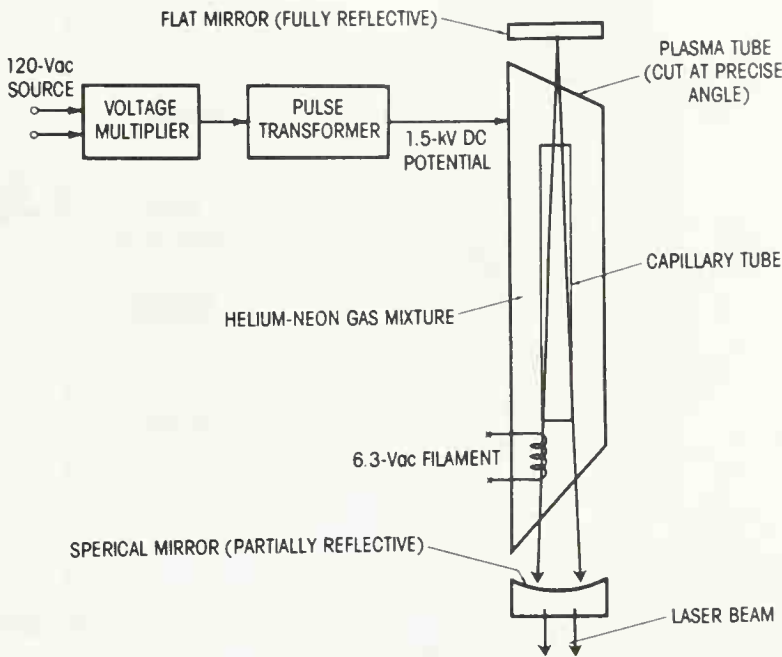
Figure 6–10. Helium-neon gas laser.
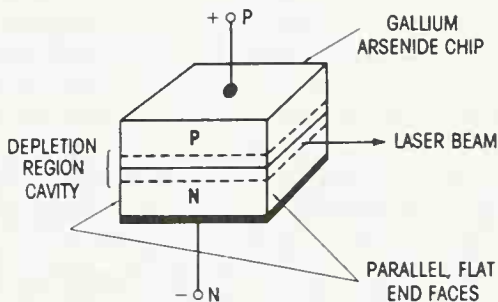
Figure 6–11. Semiconductor injection laser chip.

X-Ray Sensors

In the electromagnetic spectrum of Figure 6–1, a band of frequencies above the frequency of visible light is called X-rays. There are certain industrial control applications that utilize X-rays. A rare metal called *radium* is known to emit three kinds of rays, alpha, beta, and gamma
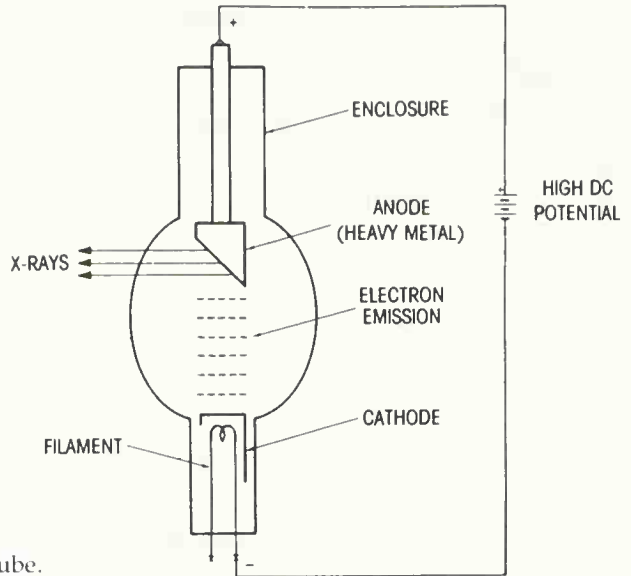
Figure 6–12.   X-ray tube.

rays. Some of these rays can pass through the human body and are frequently used in medical treatment and analysis.

It is possible to use a vacuum tube, such as that illustrated in Figure 6–12, to produce rays similar to those emitted by radium. This X-ray tube has a cathode which is heated by the application of a filament voltage. The anode is constructed of very heavy metal and has a high positive potential applied. This high positive potential accelerates the electrons emitted from the cathode at a very rapid rate. The electrons strike the anode with such velocity that X-rays are initiated away from the anode surface. If the dc potential is increased, the frequency of the X-rays will also increase (the wavelength decreases).

X-ray tubes may operate with dc potentials in excess of one million volts. The X-rays produced by this high dc voltage are similar to the high-frequency gamma rays emitted by radium. X-rays in industry are used to control industrial processes that involve metals. The short wavelength of X-rays allows them to pass through metals and reveal the inner structural characteristics of various types of metals.

Sound Sensors

Sound sensing systems rely upon the piezoelectric principle to convert sound to electrical energy. When certain crystalline materials are subjected to a mechanical stress, an electrical potential is developed across the material. Crystals such as quartz and Rochelle salt exhibit this char-
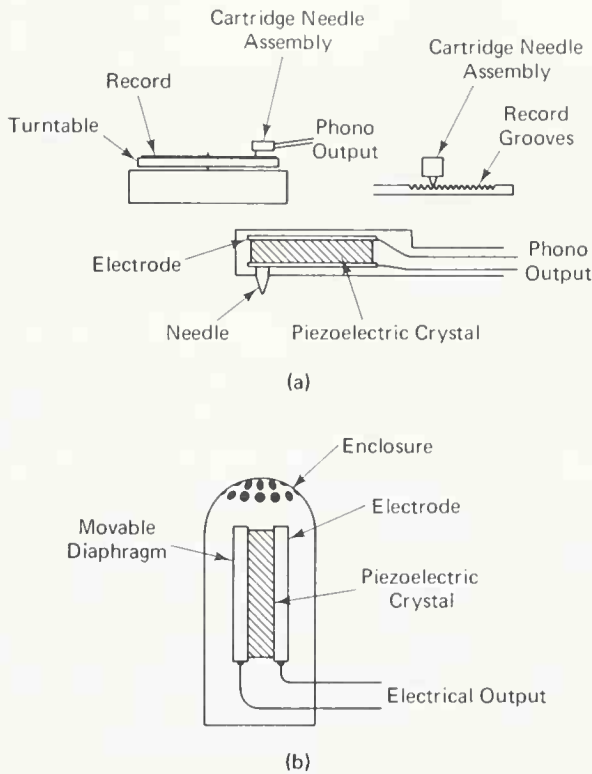
Figure 6–13. Sound sensing systems. **(a)** Phonograph cartridge/needle assembly. **(b)** Piezoelectric crystal microphone.

acteristic. An application of the piezoelectric principle for sound sensing is the cartridge/needle assembly of a phonograph (see Figure 6–13A). The cartridge contains a crystalline material which vibrates in accordance with the variations in the grooves of a phonograph record as the needle (which is attached to the cartridge) rides through the record grooves. The crystalline material develops an electrical potential across its structure due to the mechanical vibrations. These small electrical variations are then amplified by a control system. Thus, mechanical energy (vibration) is converted to electrical energy by the piezoelectric principle.

It is also common to convert sound energy to electrical energy with piezoelectric sensors. This is commonly done with crystal microphones in which sound waves cause vibration of a piezoelectric crystal (see Figure 6–13B). An electrical potential is then developed across the crystal and is amplified by the control system. Thus, variations in sound can be sensed and converted to electrical signals to accomplish control.

Heat Sensors

Sensors that produce a change in electrical output due to a change in temperature are referred to as *thermoelectric* sensors. Some sensors of this type change in electrical resistance when the temperature changes, while others produce a voltage when heated. One device used for heat sensing is the thermistor. Thermistors are temperature-sensitive resistors whose electrical resistance increases with a decrease in temperature. This is referred to as a negative temperature coefficient of resistance. Various metal-oxide semiconductor materials are used to construct thermistors, as shown in Figure 6–14.

Thermistors are manufactured in a wide range of resistance characteristics and temperature coefficients. The use of thermistors as temperature-sensing elements for industrial applications has increased in recent years.

A *thermocouple*, illustrated in Figure 6–15, consists of two dissimilar metals that are fused together at one end. The metals are usually combinations of iron-constantan, copper-constantan, platinum-rhodium, or other metals. When the fused end of the two dissimilar metals is heated, a voltage will be developed at the ends that are not connected. The voltage exists due to the different coefficients of expansion of the metals. The voltage produced by thermocouples is usually in the millivolt range. Various wire combinations are used to respond to different ranges of temperature. Thermocouples are sensors that convert heat energy into electrical energy.

WASHER

ROD
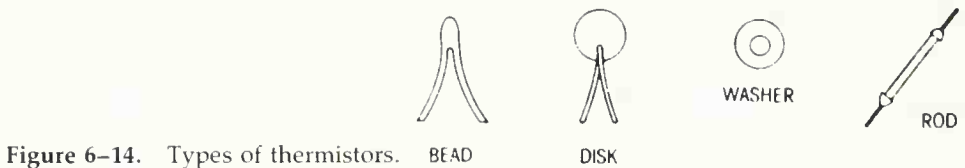
Figure 6–14.   Types of thermistors.   BEAD   DISK

TWO
DISSIMILAR
METALS

ELECTRICAL
OUTPUT

HEAT
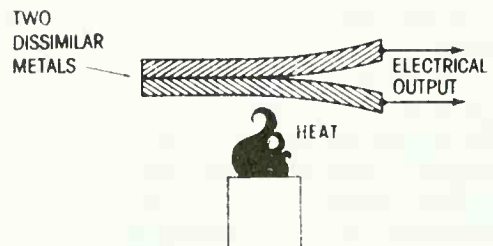
Figure 6–15.   Thermocouple.

Displacement Sensors

Displacement can be sensed by means of various types of sensors. Figure 6–16 illustrates how resistive, capacitive, and inductive sensors can be used with electrical indicators to show displacement. It is possible to sense displacements in the millimeter range or less. Displacement sensing is usually made with reference to a fixed position or with reference to the force required to move from one position to another.
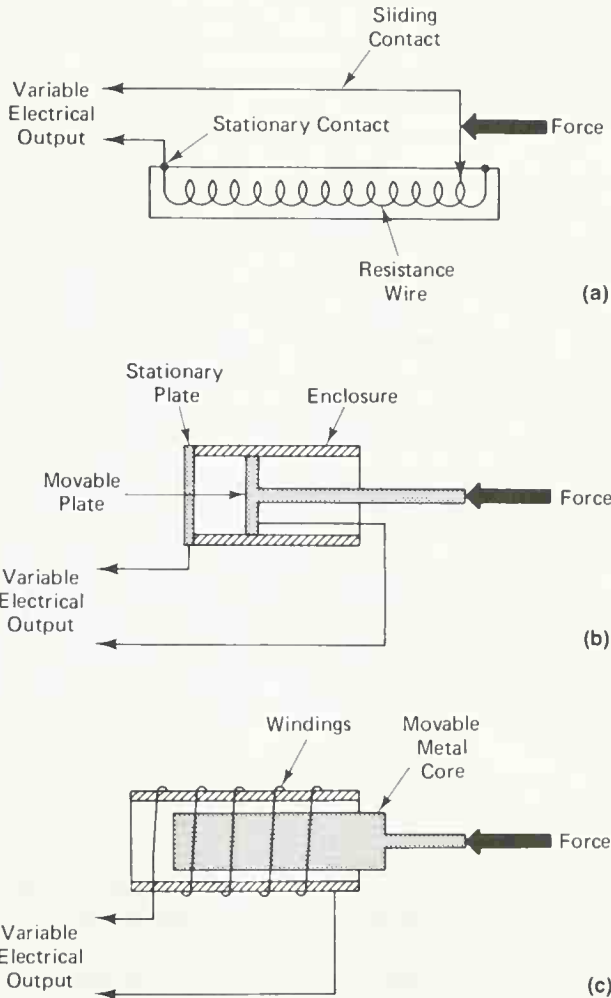
Figure 6–16. Displacement sensing systems. **(a)** Resistive sensor. **(b)** Capacitive sensor. **(c)** Inductive sensor.
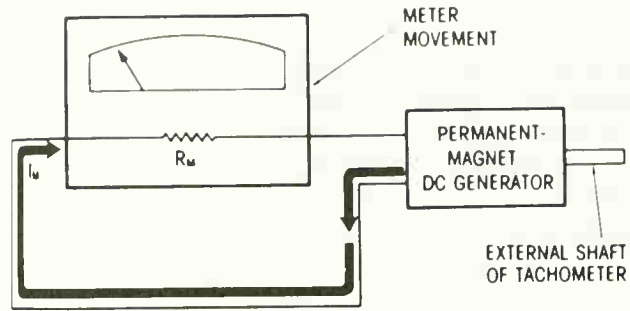
Figure 6–17.   dc tachometer speed sensing system.

Speed Sensors

Because of the nature of industrial equipment, which has shafts, gears, pulleys, and so on, speed sensing usually involves rotary movement. Several different principles can be used for sensing speed. One method is referred to as a dc tachometer system and is illustrated in Figure 6–17. This tachometer is connected directly to a rotating machine or piece of equipment. The principle involved in this system is that as the shaft of the small permanent magnet dc generator rotates faster, the voltage output increases in proportion to the speed of rotation. Voltage output increases can then be translated into speed changes or used to control equipment operation.

Electronic tachometers are now used extensively because of their increased precision and ease of usage. In the photoelectric tachometer movement is sensed by providing a reflective material on the surface of the equipment or machine where sensing takes place. The tachometer has a light source that is interrupted by the passage of the reflective material. A photocell is used to convert changes of light energy into electrical signals. The electrical signals provide a control method based on speed variations.

Mechanical Movement Sensors

Mechanical movement in the form of strain or stress can be sensed by using a device called a *strain gauge*. Strain gauges can, for example, provide electrical control signals based on the amount of pressure the mechanical fingers of a robot are exerting to lift an object.

A strain gauge such as the one shown in Figure 6–18 ordinarily is used to sense a change in dimension as some material is subjected to a stress. The strain gauge itself is constructed of fine-gauge wire about
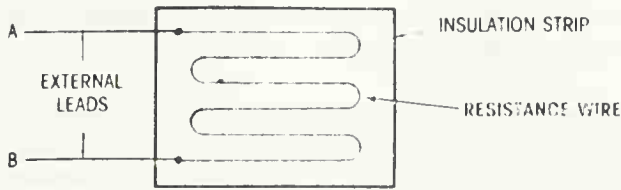
Figure 6–18.   Strain gage.

0.001 in. in diameter mounted into an insulating strip. The wire used
has a high elasticity so that it will easily change dimension. When sub-
jected to a stress, the wire is stretched. Thus, the cross-sectional area
of the wire is reduced and its length is increased. The resistance of a
conductor can be expressed mathematically as

$$R = \rho\,\frac{l}{A}$$

where

R = resistance of conductor

ρ = resistivity constant of conductor

l = length of conductor

A = cross-sectional area of conductor

Therefore, as the wire of the strain gauge is stretched, its resistance will
change due to a change in cross-sectional area or length.

More recently, semiconductor strain gauges have provided greater
sensitivity and can be used exactly like a metallic strain gauge. The rate
of change of resistance is approximately 50 times higher than in metallic
gauges. The semiconductor strain gauge is as stable as the metallic type,
but has a much higher output.

Transducers

The conversion of physical quantities to electrical quantities is a basic
sensing function. Devices that convert one form of energy into another
form are referred to as *transducers*. Transducers are devices used to con-
vert physical quantities to electrical quantities. For example, a ther-
mocouple is a transducer that converts heat energy into electrical energy.
Also, a microphone is a transducer that converts sound energy into
electrical energy. Numerous other examples of transducers are used in

homes as well as in industry. Three common classifications of transducers are (1) resistive, (2) capacitive, and (3) inductive.

Resistive Transducers.   Transducers that are considered resistive convert variations of resistance into electrical variations. One type of resistive transducer utilizes the potentiometer principle, as shown in Figure 6–19. This type of transducer changes resistance when the position of its movable contact is changed. By increasing the length of wire between terminals A and B, the resistance between those two points is increased.

A ———————————— INSULATION STRIP

EXTERNAL
LEADS

————————— RESISTANCE WIRE

B ————————————

(A) Strain gauge.

MOVEABLE
CONTACT

RESISTANCE

WIRE

STATIONARY CONTACT

—— EXTERNAL LEADS ·

A   B
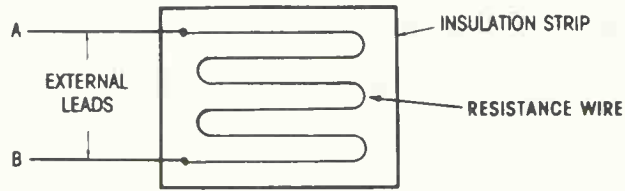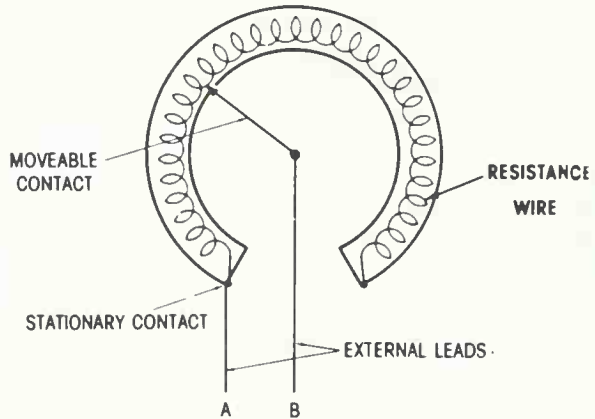
(B) Rotary potentiometric transducer.

A
EXTERNAL LEADS   STATIONARY
CONTACT   MOVEABLE CONTACT
B

RESISTANCE WIRE
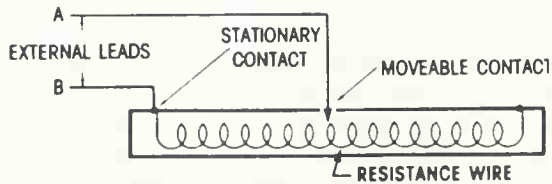
(C) Flat potentiometric transducer.

Figure 6–19.   Resistive transducers.

This principle is often used to sense physical displacement by allowing displacement to cause movement of the sliding contact.

Capacitive Transducers. Capacitive transducers rely on a change in capacitance brought about by the change of some physical quantity. Capacitance exists when two conductive materials (plates) are separated by a dielectric (insulating) material. Capacitance can be increased by increasing the area of the plates or by decreasing the thickness of the dielectric. One application of capacitive transducers illustrated in Figure 6–20 is for sensing fluid pressure. This type of transducer is placed into a fluid line. Plate 1 of the capacitor is a conductive diaphragm inserted into the fluid line to sense any variation in fluid pressure. It is electrically connected to the housing. Plate 2 is mounted adjacent to plate 1 and is initially adjusted to calibrate the indicator scale. Plate 2 is held in position, while plate 1 will vary in position due to changes in pressure. When the pressure of the fluid in the line increases, plate 1 will move closer to plate 2. Since the distance between capacitor plates is decreased, the capacitance between terminals A and B will increase. Also, when pressure decreases, capacitance will decrease. Thus, variations in pressure cause changes in capacitance.
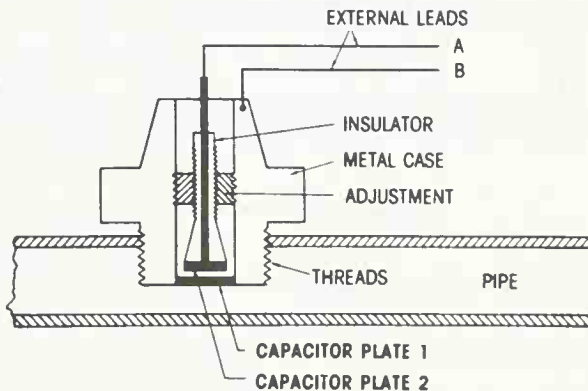
Figure 6–20. Capacitive transducer.

Inductive Transducers. Inductance can also be varied to cause an electrical change. Usually, inductive transducers such as the one shown in Figure 6–21 have a stationary coil and a movable core. The movable core can be connected to some physical variable whose movement is to be measured. As the core changes position within the stationary coil, the inductance of the coil will vary. The current flow through the coil will vary inversely with the inductive reactance of the coil, since $X_L = 2\pi fL$
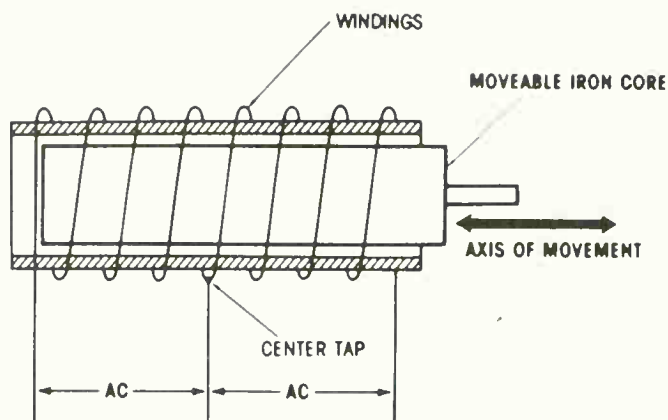
Figure 6–21.   Movable-core inductive transducer.
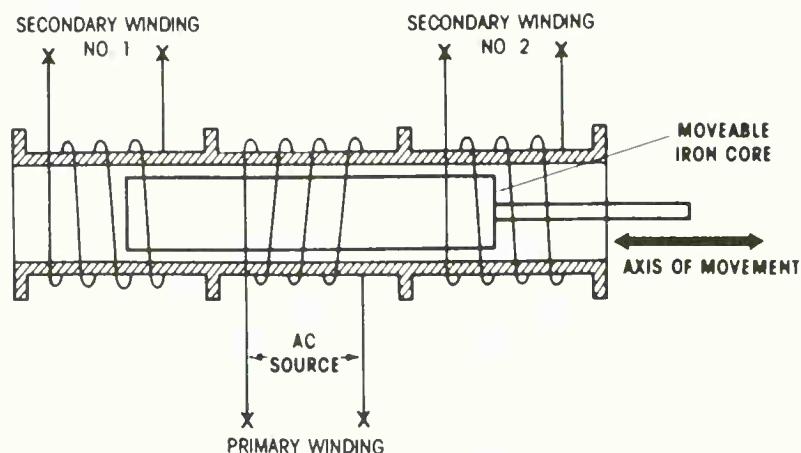
Figure 6–22.   Linear variable differential transformer (LVDT).

and $I = V/X_L$. The relative position of the core produces an electrical variation.

An often-used type of inductive transducer is the linear variable differential transformer (LVDT). The principle of operation is illustrated in Figure 6–22. A movable metal core is placed within an enclosure that has three windings wrapped around it. The center winding (primary) is connected to an ac source. The two outer windings have voltage induced from the primary winding. When the movable core is placed in

the center of the enclosure, the voltages induced in the two outer windings are equal. Any movement of the core in either direction will cause one induced voltage to increase and the other induced voltage to decrease. It is possible to sense the difference in voltage induced into the two outer windings in terms of the amount of movement of the core. The variation in magnetic coupling due to the movement of the metal core is responsible for the change in induced voltages. Thus, a linear movement (physical quantity) can be converted to an electrical quantity by this type of inductive transducer.

REVIEW QUESTIONS

1. What is the purpose of a sensing system for an industrial robot?
2. What are some types of sensors used with industrial robots?
3. What is a proximity sensor?
4. What is an optical proximity sensor?
5. What is an LED?
6. What is an eddy current proximity sensor?
7. How is a touch-sensitive proximity sensor used?
8. What is an acoustical proximity sensor?
9. What are range sensors?
10. What are tactile sensors and some examples?
11. What are visual sensors?
12. How may depth be measured by a sensor?
13. What is visual servoing?
14. What is the electromagnetic spectrum?
15. What are the three categories of optoelectronic devices? Define each category and give some examples of devices in each category.
16. What is an infrared sensing system?
17. What is an ultraviolet sensing system?
18. How is optoelectronic position sensing used?
19. What is a fiber optic system?
20. How may laser sensing systems be used in industry?
21. What are some types of laser systems?
22. How may X-rays be used in industrial control?
23. What is a sound sensing system?
24. Discuss the two types of heat sensing systems.

25. Discuss a method used for speed sensing.
26. Discuss the strain gauge as a means of mechanical movement sensing.
27. What is a transducer? List three types.

FLUID POWER SYSTEMS

Systems designed to transfer power through fluids are very important in automated manufacturing systems and industrial robots. The term *fluid* is a general classification for systems that use air, oil, or a combination of air and oil. The term *hydraulic* is used to describe systems that use only liquids or fluids. Systems operated with air only are usually described as *pneumatic*. The operating principles associated with these systems are similar in many respects. Figure 7–1 shows a fluid power system with the basic parts labeled.

Fluid power systems often use electrical energy to produce rotary motion to energize fluid pump. Electrical energy or mechanical motion is converted into the energy of a flowing fluid. Fluid power systems are quite reliable and have a great deal of flexibility. Power can be transferred to any location where a pipe, hose, or piece of tubing can be placed. The symbols used for fluid power systems contained in Appendix should be reviewed.

Hydraulic Systems

Hydraulic systems are commonly found in automatic machinery control and in material-handling equipment. The popularity of this type of system can be attributed to such things as operational simplicity, smoothness of operation, reliability, and adaptability. Figure 7–2 shows a type of hydraulic system used to control a punch-press ram.
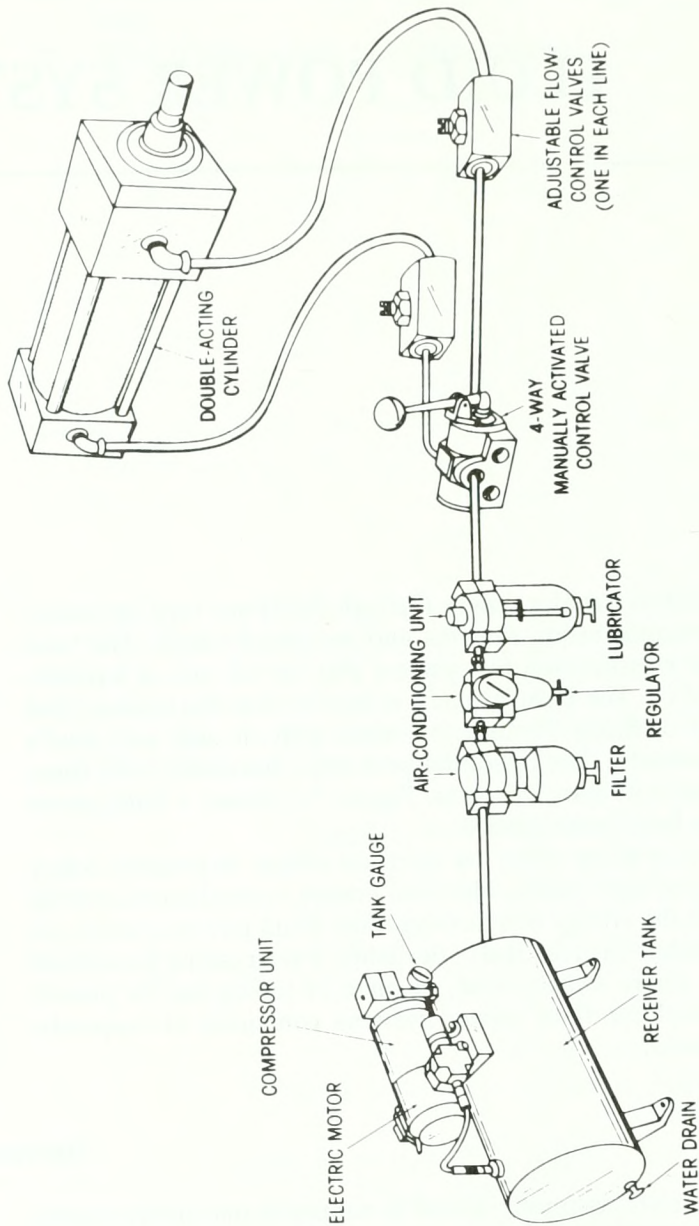
Figure 7-1. Pneumatic fluid power system.
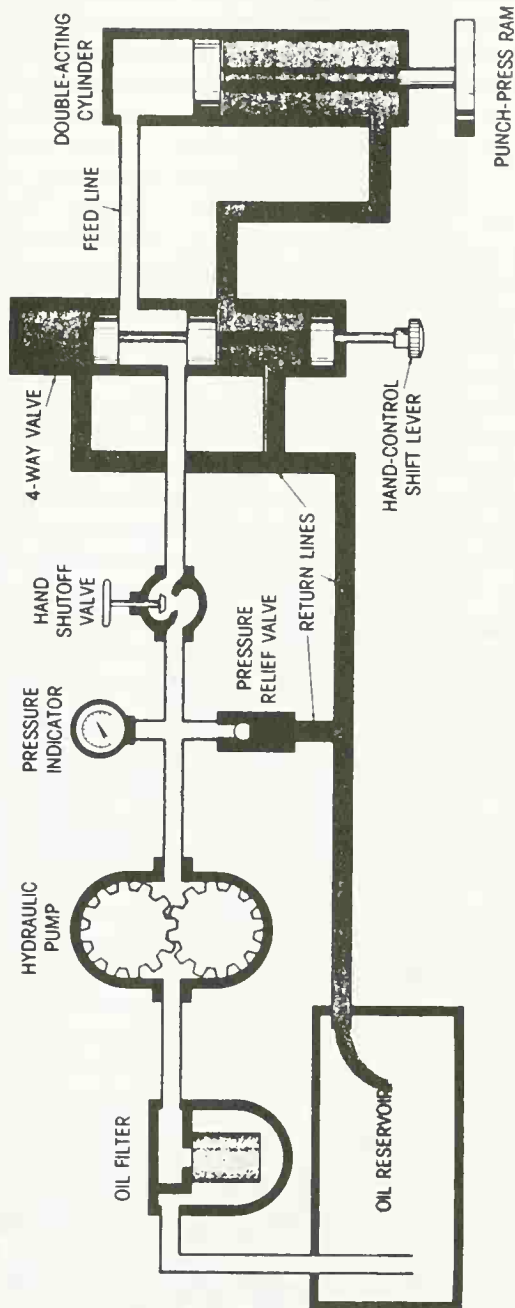
Figure 7–2. Hydraulic fluid power system.

The energy source of the hydraulic system in Figure 7–2 is an electric-motor-driven pump and the reservoir. Rotary mechanical energy of the motor is changed into fluid energy through this device. During the pump's operation, fluid is set into motion. Fluid entering the inlet port is set into motion and forced through the outlet port. With each revolution of the pump rotor blade, a fixed amount of fluid is forced into the system. Fluid entering the system then encounters resistance to its flow, which creates hydraulic pressure. Figure 7–3 shows a simplification of the internal workings of a hydraulic pump.

The transmission path of a hydraulic system is typically solid pipes or some form of flexible tubing. Hydraulic fluid forced to pass through the transmission path encounters a resistance to its flow, which builds up system pressure. Both single-pressure and high/low-pressure systems are available.

The hydraulic system of Figure 7–2 has various ways to control the system fluid. The hand shutoff valve permits control of the system by stopping the fluid flow through the transmission line. The pressure of the system can be altered by changing the operating speed of the motor-driven pump. The four-way valve of the system also has a control function. It can be positioned to have control that restricts the amount of fluid reaching the cylinder. Secondly, it can be made to alter the flow path of the fluid. Fluid flow can also be stopped completely by placing the shifter lever of the valve in its off position. The pressure relief valve is a control device that protects the system automatically. Running the pump with the hand valve closed would ordinarily cause the relief valve to open and return high-pressure fluid into the reservoir.

The load of a hydraulic system is the part of the system that does work. In Figure 7–3 the double-acting cylinder serves as a load device of the system. This part changes the mechanical energy of hydraulic fluid flow into linear motion that moves the ram of a press. Pressure applied by the ram to an outside workpiece also alters the load to some extent. Hydraulic motors are also used as a load in some systems to produce rotary motion.
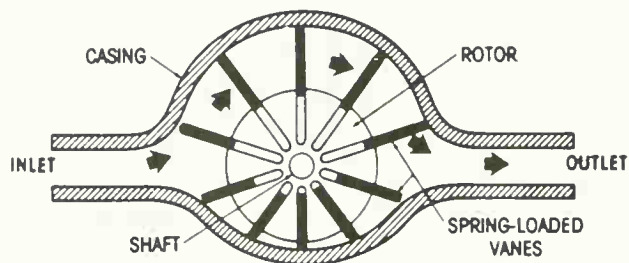
Figure 7–3. Internal workings of a hydraulic pump.

The indicator of the hydraulic system in Figure 7–2 is an optional item, as it is in other systems. In this application the indicator is used to show system pressure. Monitoring the fluid pressure and maintaining it at a constant level ensures consistent operation of the system.

Pneumatic Systems

Pneumatic systems are used in industry to power hand tools and to lift and clamp products during machining operations. The energy source of this type of system is a pump or a compressor and a storage tank to hold the air. The pump of a compressor may be driven electrically by a motor or by a portable internal combustion engine. Figure 7–4 shows a simple pneumatic system driving a double-acting cylinder ram.

Pneumatic systems are designed to use the air from the room where the compressor of the system is located. Through the action of the pump, outside air is forced into a tank under pressure where it is stored or passed through the system. The storage tank of compressed air serves as the reservoir of this system.

After air has been compressed, it must be conditioned before it can be used by the system. Conditioning takes place for the removal of dirt and moisture. This is achieved by an air filter with a condensation trap and drain. A fine mist of oil may then be added to the compressed air. This provides lubrication for all parts throughout the system. The pressure of the air must be adjusted to a specific level by an air-regulating valve. Constant pressure must then be maintained during system operation. Motor-driven air compressors are designed to operate only when the system pressure of the storage tank drops below a predetermined level.

The transmission path of a pneumatic system consists of solid pipes, tubing, and flexible hoses that are generally used as feed lines from the compressor to different parts of the system. Return lines to the storage tank, however, are not used in pneumatic systems. Air is simply dumped from the system into the atmosphere. Pneumatic systems are somewhat simplified because of this feature.

The pneumatic system of Figure 7–4 has several methods to control the system air. The hand shutoff valve and pressure-relief valve provide control of air circulating through the transmission path. Air flow can also be altered by the regulator and the three-way valve. Pneumatic and hydraulic controls are very similar.

The load of a pneumatic system, as in other systems, is designed to perform a work function. The primary load device of Figure 7–4 is the pneumatic cylinder. This part changes the mechanical energy of air into linear motion that drives a press ram. Pressure applied by the ram
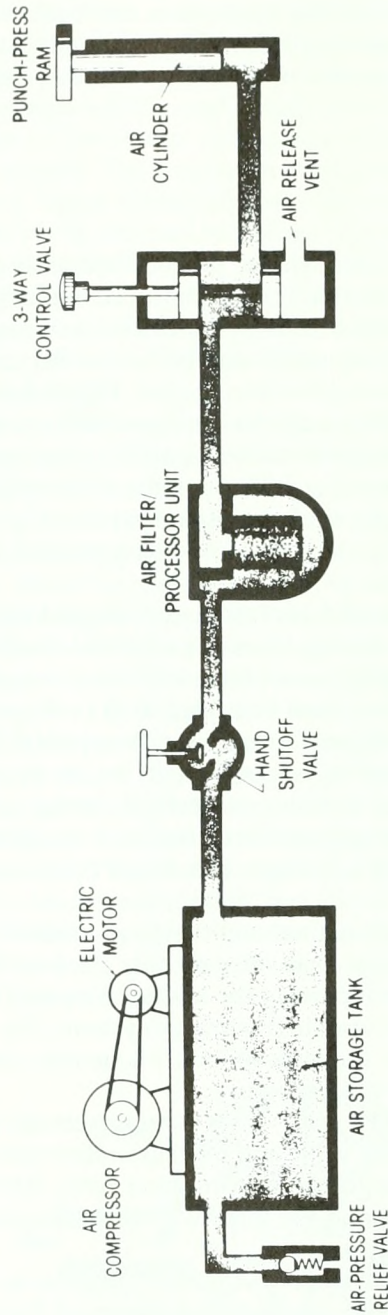
Figure 7-4. Simple pneumatic system.

to an outside workpiece also influences the load to some extent. Pneumatic load devices can also be used to produce rotary motion.

The indicator of a pneumatic system is usually an optional item. It is commonly added to the system to monitor tank pressure. Regulator output pressure is also monitored with an indicator so that exact system pressures can be determined. Test indicators are frequently used in pneumatic systems to troubleshoot faulty components.

Fluid Power System Applications

Applications of fluid power systems are so numerous that it is difficult to subdivide them. A large part of all fluid power system applications used in industry today utilize electrical energy. Fluid power systems represent a very important part of all mechanical power system applications in industry today. The term *fluid* refers to both hydraulic and pneumatic system applications. These systems are very similar in many respects. There are, however, many unique differences and applications of both system types found in industry. Fluid basics will be discussed, pointing out some of the common principles that apply to both system types. Specific hydraulic and pneumatic system applications will then be investigated as they apply to unique industrial applications.

A number of sophisticated industrial systems have recently been developed that produce mechanical energy through a combination of both fluid and electrical system applications. Hybrid systems of this type are playing a very important role in automated manufacturing. A person working with automated manufacturing systems must be familiar with both fluid and electrical system basics in order to understand the operation of many types of industrial systems, including robotic systems.

Fluid power systems are responsible for developing a useful form of mechanical power through the transmission of a fluid through a system. Systems of this type are useful in transferring power to inaccessible locations over moderate distances. A very fine degree of control can be achieved that has a wide variation of speed capabilities and a reversing capability. In many system applications fluid power represents the only practical solution to mechanical power transmission.

Fluid power systems have a number of characteristics that distinguish them from other power systems. A very small force of a few ounces, for example, has the capability of controlling a larger force of several tons. Through the use of computer-controlled machines, fluid power systems can provide changes that will cause movement within tolerances of plus or minus one ten-thousandth of an inch. Fluid power systems can also provide rotary motion at extremely high speeds or can develop creeping speeds of only a fraction of an inch per minute. Fluid

power systems are very compatible with other systems, for example, electrical, digital, or mechanical control methods. Fluid systems are efficient, dependable, easy to maintain, and economical to operate for long periods of time. A high percentage of all the machine tools used in industry are controlled or operated by fluid power.

The Fluid Power Principle

Nearly everyone working in industry has had an opportunity to see a fluid power system in operation at one time or another. An example of the fluid power principle is found in automobile service stations that have hoists to lift cars for servicing. A system of this type ordinarily uses both air and oil to develop the power needed to lift an automobile.

An automobile hoist operates on the principle that air added to the top of a long cylinder confined in an oil-filled tube can be forced to move upward under pressure. The tube and cylinder are normally placed in the floor of the station in such a way that the entire unit will retract when air pressure is removed. The cylinder will rise out of the floor when air is forced into it through the action of a control valve. The air source is developed by an electric-motor-driven compressor. Full control of the hoist is achieved by manual manipulation of the air valve by the operator. Figure 7–5 shows a simple fluid power system automobile hoist.
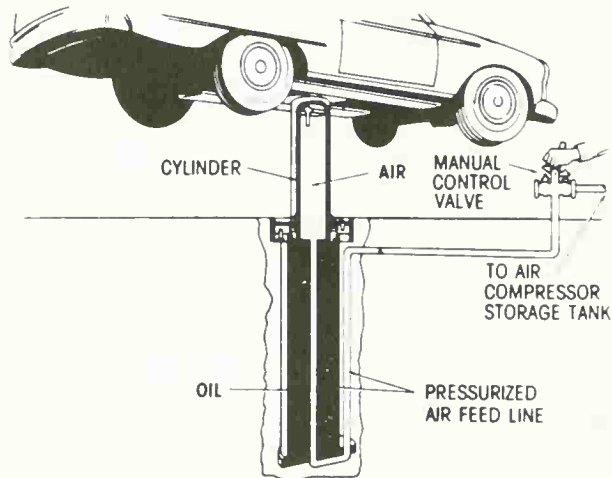
Figure 7–5.   Fluid power automobile hoist.

In 1653 a French scientist named Blaise Pascal discovered a simple physical law: "A pressure applied to a confined fluid is transmitted undiminished throughout the fluid. It acts on all surfaces in a direction at right angles to those surfaces." This statement eventually became known as *Pascal's law*. Air and hydraulic fluid both respond to the basic principles set forth by this law. Pascal's law, therefore, serves as the basic premise of all fluid power systems.
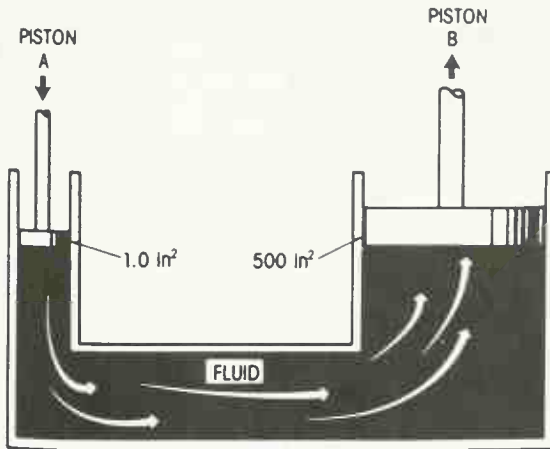
Figure 7–6. Illustration of Pascal's Law.

Figure 7–6 shows a graphic example of Pascal's law. The force applied to the fluid inside of the cylinder at piston A is instantly transferred to all parts of the cylinder. Piston B moves an amount that is equal to the force originating at A. This action occurs when both pistons are of the same physical size. The fluid of this sytem easily conforms to the inside shape of the cylinder. The same force acting on piston B is also applied to the inside walls of the cylinder. The strength of the cylinder walls must also be capable of withstanding this amount of pressure.

Force, Pressure, Work, and Power

The *force* applied to the piston of the system just described is defined as any cause which tends to produce or modify motion. To move a body or mass, an outside force must be applied to it. The amount of force needed to produce motion is primarily based on the inertia of the body. Force is normally expressed in units of weight. Weight is defined as the

gravitational force exerted on a body (or mass) by the earth. Since the weight of a body is a force (not a mass), we must use units of force to express both weight and force. The basic unit of force in the English system of measurement is the pound (lb). In the International System of Units (SI), or metric system, the basic unit of force is the newton (N).

Pressure is a term used to describe the amount of force applied to a specific unit area and is expressed in pounds per square inch (lb/in.^{2}) in the English system or as newtons per square meter (N/m^2) in the metric system. The unit pascal (Pa) has been assigned as the basic unit of pressure in the metric system (1 Pa $=$ 1 N/m^2). At sea level the pressure of the atmosphere on the surface of the earth is 14.7 lb/in.^{2}. In industrial applications, giant hydraulic presses are capable of squeezing metals with a pressure as great as 100×10^6 lb/in.^{2}. Mathematically, pressure is expressed as

$$P = \frac{F}{A}$$

where

$$P = \text{pressure, lb/in.}^2 \text{ or Pa}$$

$$F = \text{force, lb or N}$$

$$A = \text{area, in.}^2 \text{ or m}^2$$

An interesting and important fact about force and pressure is that they only represent a measure of *effort*. A measure of what the system actually accomplishes is called *work*. In the fluid system just described work is accomplished when the force applied to piston A causes it to move a certain distance. Work is commonly expressed in foot-pounds or newton-meters (joules). The mathematical formula for this relationship is

$$W = F \times D$$

where

$$W = \text{work, ft-lb or N-m (J)}$$

$$F = \text{force, lb or N}$$

$$D = \text{distance, ft or m}$$

A more realistic concept of work must take into account the length of time that it is being accomplished. The term *power* is commonly used to express this relationship. The term *horsepower* is also commonly used in industry to express mechanical power. Moving 33,000 pounds a dis-

100-lb. Force
Piston A

1.0-in² Area

When Piston A Moves 4 in.
it Causes Piston B to
Move Only 0.04 in.

100 lb/in²

4 in.

10,000 lb of Force
Piston B

100-in² Area

0.04 in

100 lb/in²

100 lb/in²
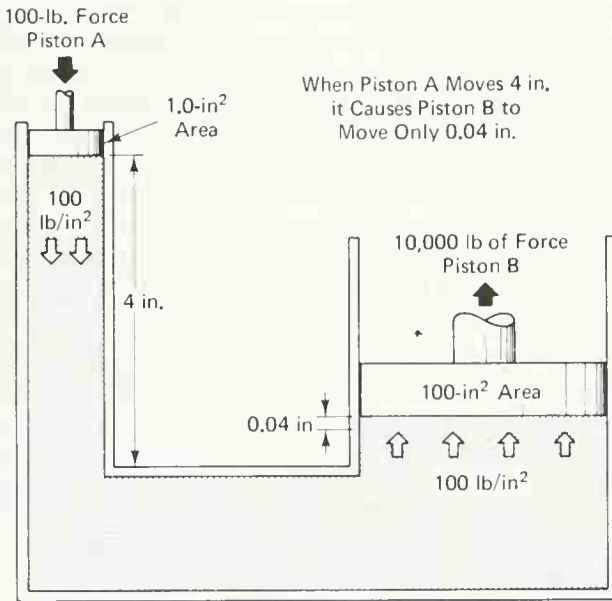
Figure 7–7. Illustration of static fluid power system.

tance of 1 foot in 1 minute or 550 pounds a distance of 1 foot in 1 second is a physical expression of horsepower. Electric motors are rated in horsepower or fractional values of horsepower.

A Simple Fluid Power System

A very simple static fluid power system is illustrated in Figure 7–7. In this system a 100-lb force is applied to piston A, which has an area of 1.0 in.². A pressure of 100 lb/in.² is developed by this action and is transferred through the fluid to piston B. The area of piston B is shown to be 100 in.². Since the transfer of pressure through the fluid is equal to all parts of the cylinder, each square inch of piston B will receive 100 lb of force. As a result, 100 lb/in.² × 100 in.² equals 10,000 lb of force applied to piston B.

The distance that piston B moves is directly proportional to the area ratio of the two pistons. Moving the 1-in. piston 4 in. into the cylinder forces 4 in.³ of fluid to be displaced. This displaced volume of fluid is based on the area of the piston times the distance it moves into the cylinder. Therefore, 1 in.² × 4 in. = 4 in.³ of fluid displacement. Spread over the 100-in.² surface of piston B, this displacement causes piston B to move only $\frac{1}{100}$ of the distance traveled by piston A. In this case, $\frac{1}{100}$ of 4 in. only equals 0.04 in. of motion. Piston B, therefore, has

more force applied because of its size but travels only a small distance. The amount of work done by pistons of a static fluid power system shows an unusual relationship. The work done by piston A is 100 lb × 4 in., or 400 in.-lb. At piston B the amount of work achieved is also 400 in.-lb. This is determined by multiplying the applied piston force by the distance moved. Therefore, 10,000 lb × 0.04 in. = 400 in.-lb of work.

In actual practice, fluid power systems do not show a 100 percent transfer of power from input to output. Fluid moving along cylinder walls, for example, encounters a form of surface friction. The amount of power loss developed by this friction appears primarily as heat developed on the walls of the cylinder. In a static power system the amount of power loss due to heat is so small that it would be considered negligible. In systems that move larger volumes of fluid over longer lines, losses of this type become an important consideration. As a general rule, excessive friction losses can be controlled by reducing the line length, keeping the number of bends at a minimum, and preventing excessive fluid velocity by selecting proper-size distribution lines. Proper design generally takes these things into account so that a high level of system operating efficiency can be achieved.

Fluid Flow Characteristics

As fluid flows through the components of a power system, it encounters a certain amount of opposition due to friction. In a fluid system this opposition is generally called resistance. System pressure is developed as a result of fluid being forced against the resistance of surface areas of system components. A direct relationship, therefore, exists between system pressure and component resistance.

Figure 7–8 illustrates the friction-pressure relationship of a static fluid power system. The pressure at point F is referenced at zero because the friction offered to fluid flow at this point is zero. A break in the system could cause this condition to occur. Other parts of the system show varying degrees of pressure change according to system resistance. Point B represents the highest pressure area of the entire system because the full weight of the fluid appears at this point. Fluid flowing from point B to point F must change all of its potential energy into heat energy. The moving fluid in this case also causes a drop in pressure as it passes from points B to F. This pressure drop increases at each location point beyond B. At the same time, the source pressure decreases at each point an equal amount. Pressure drops of this type are undesirable when power is being transferred through a system. In some applications a drop in pressure is often used to trigger the starting of a second operation in a sequential system.
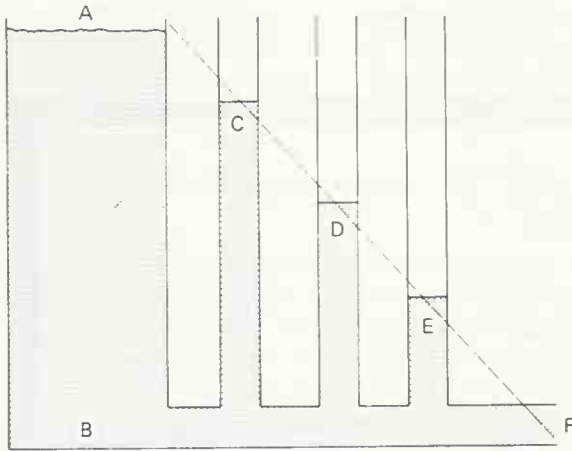
Figure 7–8. Illustration of the friction pressure relationship of a static fluid power system.

Pressure drop is also a very important characteristic in a flowing fluid power system. This condition is much more significant than that of the static system just discussed because nearly all industrial systems respond to flowing air or fluid. Pressure drops of this type can be caused by flow turbulence created where abrupt changes in direction occur. Refer to the corners of the system in Figure 7–9. System restrictions encountered by fluid flow are also a source of pressure drop. Control valves and tubing sizes are largely responsible for this type of drop. Small lines tend to increase the speed of fluid flow, which in turn causes an increase in surface friction. Notice the pressure drops near each of the restricted areas of Figure 7–9. The length of a system line is another important pressure drop factor that must be considered. In this case fluid sees more resistance when it travels long distances. Proper system design usually minimizes this factor. A very interesting thing to note about pressure drop takes place when the flow ceases. Pressure drop, in this case, stops and the pressure reaches a stable value throughout the system. A faulty pump or loss of electricity could cause this condition to occur. By comparison, a break in the system line normally causes a complete loss of pressure or a very pronounced change in pressure value. These two pressure conditions are very evident when compared with the characteristics of a normally operating system.

Compression of Fluids

The preceding information could apply to both hydraulic and pneumatic systems. Compression of system fluid, however, represents a major dif-
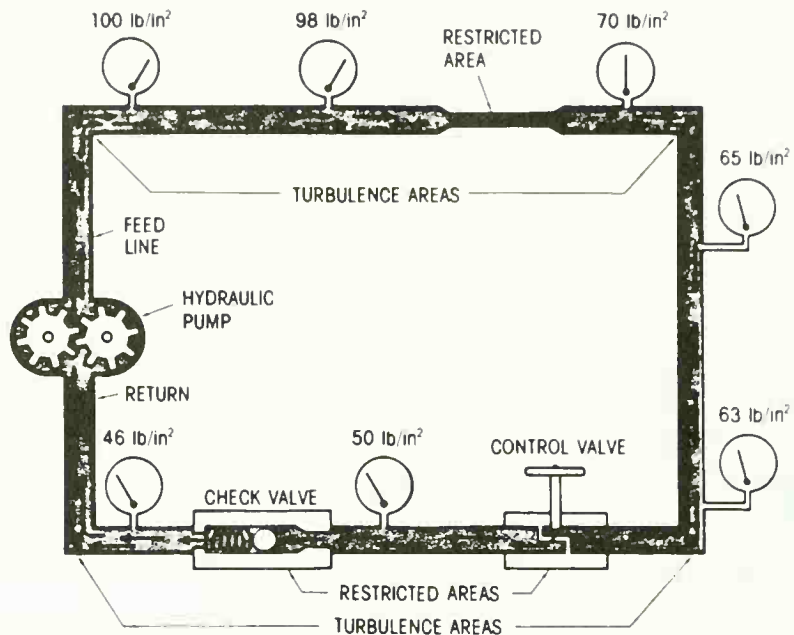
Figure 7–9.   Illustration of pressure drops around a flowing fluid power system.

ference between the two systems. In general, we can say that all gases and liquids are compressible under certain conditions. In a hydraulic system oil is used to transfer power throughout the system. Ordinarily, a hydraulic fluid is not compressible except in extremely long transmission lines or under rather high pressures. Under normal operating conditions compression of a hydraulic fluid is not considered to be a real problem. A volume reduction of approximately 0.5 percent for every 1000 lb/in.^{2} of pressure is typical. In most industrial applications, this amount of hydraulic fluid compression is not considered significant.

Fluid power systems of the pneumatic type are primarily designed to respond to fundamental laws that apply specifically to gaseous fluids. Industrial applications of this type nearly always use air as the operating medium. Air must first be compressed by the system source before it can be effectively used to transmit power. When air is reduced in volume by the compression process, its pressure increases. Compressed air is produced, stored in a tank, and then released into the system when it is needed. Pneumatic systems normally release air into the atmosphere after it has been used by the system.

Fluid compression represents a major difference between hydraulic and pneumatic power systems. Hydraulic fluid is not compressed under normal operating conditions to any great extent. Pneumatic systems, by

comparison, respond only to compressed gases and primarily to air. Because of this basic difference, there are some unique physical features in system components. As a general rule, however, the basic function of each component is similar for both hydraulic and pneumatic systems.

Industrial Hydraulic Systems

Most of the hydraulic power systems used in industry today are of the circulating fluid type. This type of system employs a hydraulic pump as a power source to move the fluid. The pump is driven by mechanical energy that has been produced electrically. Hydraulic fluid under pressure is made to circulate through the transmission lines, or pipes, of the system in a ready state of operation. System control is achieved by such things as directional valves, metering devices, flow control valves, and regulators. The load of this system is primarily designed to do some type of useful work. Mechanical motion produced by the load is either rotary or linear. Cylinder actuators and hydraulic motors are typical components that achieve this function. A number of hydraulic indicators are also used to show different operating conditions and to test system components. Pressure, temperature, and flow are typical system values monitored by indicators. Typical parts of a hydraulic unit are an electric motor, a hydraulic pump, a pressure relief valve, gauges, and a reservoir. The primary energy source of a unit is electricity. Electricity must first be changed to mechanical energy through rotation of the motor. The motor, in turn, is used to drive the pump. Hydraulic fluid from the pump then circulates through the system and builds up pressure.

Most of the hydraulic power systems used in industrial applications today are equipped with a filtering device. The hydraulic fluid is filtered before it has an opportunity to enter other system components. Any dirt particles coming from the pump or reservoir are removed from the fluid flow before entering the remainder of the system. Filtering of a hydraulic system reduces component breakdown.

Filtering devices can also be placed in the return line to remove dirt from the fluid after it passes through the system. One theory for placing the filter in this location is that fluid dirt is more prevalent in system components that move. In complex hydraulic systems with numerous components, filters may be placed in both the feed and return lines to reduce contamination problems.

Control of a hydraulic power system is achieved by a number of different valves. These include check valves, reducing valves, directional valves, relief valves, and flow control valves. Some of these are manipulated manually by an operator, electrically by solenoid devices, or automatically by pressure changes. In addition to this, valves can be

tripped by an outside air source, temperature changes, or through the mechanical action of devices at different system locations. The control function of a hydraulic system is undoubtedly the most complex function of the entire system.

The load of a hydraulic system typically could be double-acting cylinders connected to the cylinder lines. When high-pressure oil from the feed line is applied to a cylinder, it causes the piston to be thrust forward. Any oil on the front side of the piston is forced into the return line by this stroke of the piston. Reversing the oil flow from a directional control valve causes the action of the piston to be reversed. Mechanical motion of this type can then be harnessed to do some type of useful work for automated manufacturing.

Industrial Pneumatic Systems

The pneumatic system of Figure 7–10 is often used for small industrial applications. The air-compressor unit serves as the source for the entire system. Typically, this unit employs electrical energy to produce rotating mechanical energy through the action of the motor. The compressor of this unit is driven by the motor. Compressed air is then stored in a receiving tank where it is eventually distributed to the system when needed. Receiver tank pressures range from 100 to 150 lb/in.^{2}, as indicated on the tank pressure gauge. The feed line of the entire system is connected to the receiving tank for distribution throughout the plant.

Pneumatic systems must also employ some type of air-processing components in order to condition the air before it can be used. In systems with a small number of components, one conditioning unit is adequate. Systems with a large number of components often connect these units to each load device attached to the feed line. Conditioning the air involves filtering, pressure regulation, and lubrication. As a general rule, a conditioning unit is connected in the feed line between the compressor and the first control device.

Control of the pneumatic system of Figure 7–11 is achieved by a manually operated, four-way control valve. Air flow to the cylinder can be directed to cause forward or reverse motion, or it can be turned off by the control valve. One line to the cylinder will receive air and the other line will exhaust air into the atmosphere through the control valve. Exhausting air instead of returning it to the system is a unique characteristic of the pneumatic system.

Most pneumatic systems used in industry today employ adjustable air flow valves to each load device. These devices are often placed in both lines, as indicated in Figure 7–10. Valves of this type are designed to regulate the actuating speed of a cylinder. By using a valve in each

PACKAGING
MACHINE

PNEUMATIC
VALVE

CYLINDER

CONVEYOR
SYSTEM

AIR PROCESSING
UNITS

MOTOR-DRIVEN
AIR COMPRESSOR

RECEIVING
TANK
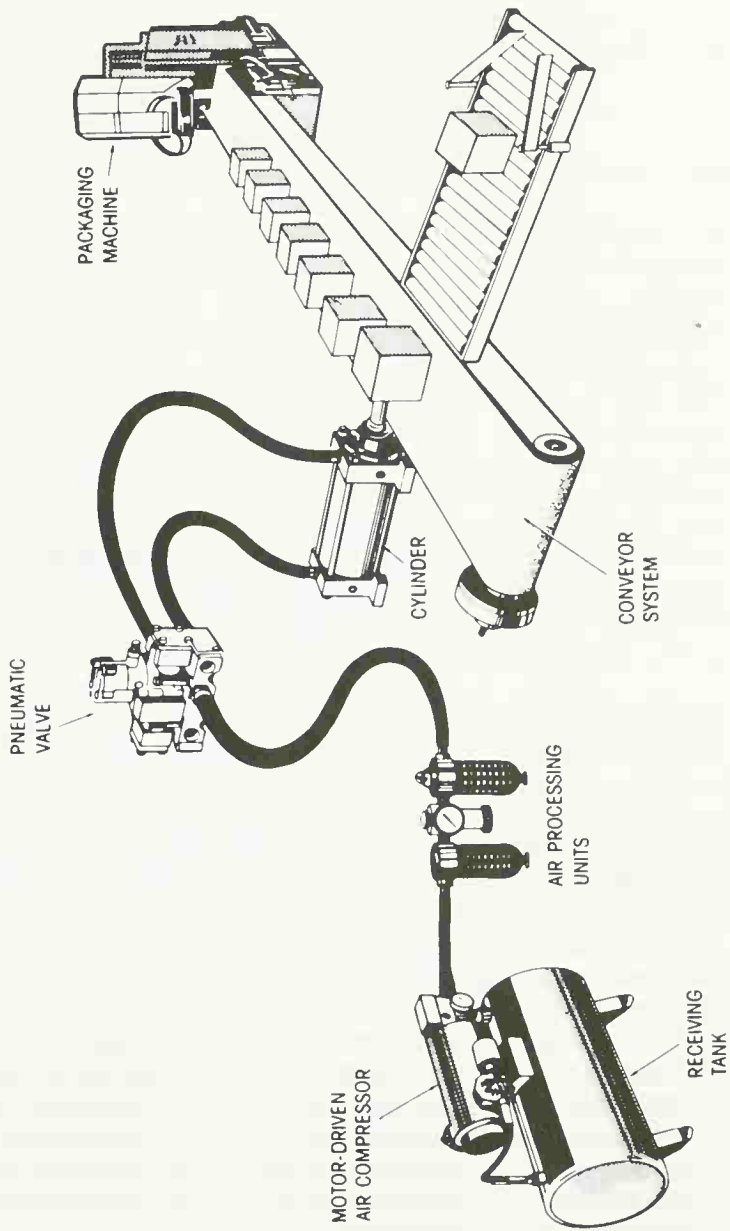
Figure 7–10. Industrial pneumatic system.
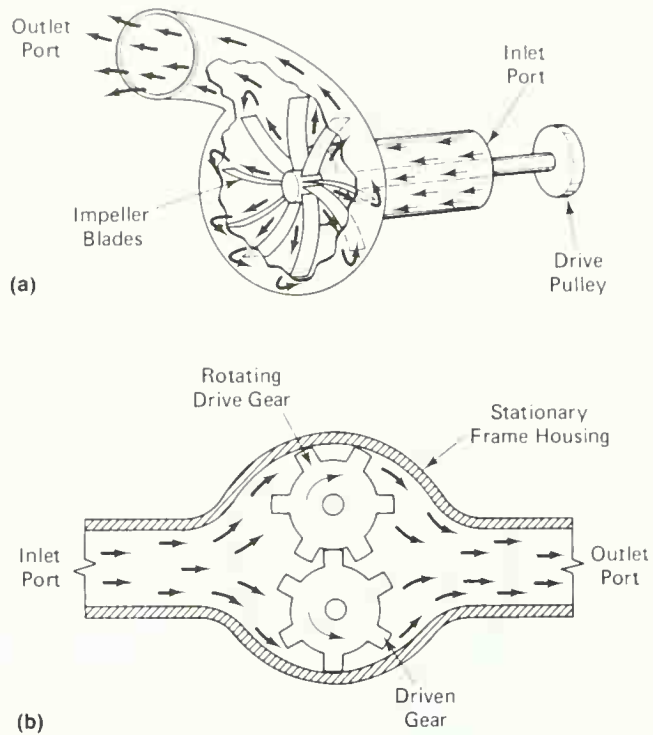
Figure 7-11.   Illustration of the two general classifications of pumps. (a) Non-positive displacement type. (b) Positive displacement type.

line, cylinder operation can be made to respond to a variety of action combinations. Without this control, the cylinder would receive maximum air pressure from the system. This would, of course, cause high-speed mechanical action of the cylinder from one position of the piston to the other. Adjustable air flow valves add a great deal of versatility to the mechanical action of the load device.

The load device of the pneumatic system in Figure 7-10 is designed to produce linear mechanical motion. In this case the cylinder is of the double-action type. It can be made to move in a forward or a reverse direction according to the air flow from the control valve. Pneumatic load devices are also designed to produce rotary motion. Air motors and rotary actuators are commonly used to achieve this operation in automated industrial applications.

Most of the pneumatic systems used in industry today employ several indicators placed at strategic locations throughout the system. System pressure, as a general rule, is monitored by this type of indicator.

The regulator and receiving tank of the pneumatic system in Figure 7–10 both employ pressure gauges as indicators. Pressure drops along the system feed line can also be monitored by observing pressure readings at key locations. System maintenance and troubleshooting generally rely heavily on the use of indicators to locate faulty components.

Fluid System Components

The term *fluid system* is a generic term used to describe both hydraulics and pneumatics. In this section a discussion is presented of discrete components that are used with automated manufacturing systems. There is a great deal of similarity in these components. In some instances hydraulic and pneumatic components can even be used interchangeably. Hydraulic components are generally somewhat larger than their pneumatic counterparts and tend to be a bit more rugged in construction. These differences can primarily be attributed to the fact that air is less dense than oil. It takes larger volumes of air to transmit equal values of pressure and force. Hydraulic systems, by comparison, tend to be used in applications that demand high pressure levels for heavy-duty automated machine operations. Except for the differences in size, ruggedness, and pressure, hydraulic and pneumatic components operate on the same basic principles and respond in a similar manner.

Fluid Pumps

The pump of a fluid system is often called the heart of the entire system. It is designed to provide the system with an appropriate fluid flow that will develop pressure just as the heart of the human body does. In a fluid system the pump accepts mechanical power from a drive motor and converts it into an equivalent amount of fluid power.

Basically, a pump is a device that accepts fluid at an inlet port, forces it to move through a confined area, and expels it from an outlet port. Air and gas may be compressed into smaller volumes through this process, which tends to increase the pressure. Oil and liquids are forced to flow at a faster rate, causing pressure to develop in a system. In practice, the specific application of a pump in either a pneumatic or a hydraulic system determines the actual role that it must play.

Hydraulic pumps are primarily classified as *continuous-operation* pumps. In this capacity they must keep the fluid in a constant state of motion whenever the system is in operation. A pneumatic pump, by comparison, is better described as an *air compressor*. As such, the pump causes air to be squeezed into a smaller volume and forced into a receiving tank for storage. When the tank pressure builds up to a certain

level, the compressor pump is turned off. Compressors are often used for short operational periods. These occur only when the demand for system air arises during machine operation.

There are two general classifications of pumps used in fluid system applications. The first classification is called a *nonpositive displacement pump*. This pump has no set amount of air or fluid that will be passed by the impeller blades during rotation. Flow is directly dependent upon the speed of the impeller blades. The second classification is called a *positive displacement pump*. This pump has a rather close clearance between the rotating member and the stationary components. As a result of this construction, a definite or positive amount of fluid will pass through the pump during each revolution. Figure 7–11 shows a comparison of these two pump classifications.

The application of fluid pumps in automated manufacturing is so varied that it is difficult to list all of the different types used. A few basic pump types will be discussed to provide an understanding of industrial pump applications. Four basic pumping methods are commonly found in automated manufacturing systems. Of these, three are positive displacement types and the fourth is of the nonpositive displacement type.

The reciprocating motion of a piston is often used in many high-volume and pressure pumping applications. Rotary motion is commonly used to produce pumping action. Gear and vane pumps operate on this principle. These pumps are available in a wide variety of designs and styles and represent the most common of all pump types. The final type of pump which is discussed uses centrifugal force to drive an impeller blade. This pump is more speed dependent than the other basic types. Each pumping method discussed is unique and has many industrial applications.

Reciprocating Pumps.   A common type of industrial pump used in both hydraulic and pneumatic applications operates on the reciprocating principle. This pump forces either air or oil from a chamber by the reciprocating action of a moving piston. During the intake stroke air or oil is drawn into the chamber through an intake valve. A partial vacuum inside the chamber is created by the piston as it is being pulled to the bottom of its stroke. In this condition of operation the intake valve is pulled open, thus admitting air or oil into the chamber. The chamber is filled to capacity by the time the piston reaches the end of its stroke. Figure 7–12A shows this operational step.

When the piston reaches the bottom of its stroke, the action is reversed. In this case the rotary motion of the motor causes the piston to change direction because of its eccentric connection to the drive disk. This action forces the discharge valve open and closes the intake valve. As a result, oil or air is forced out of the chamber. Figure 7–12B shows this operating condition with the piston near the top of its stroke.
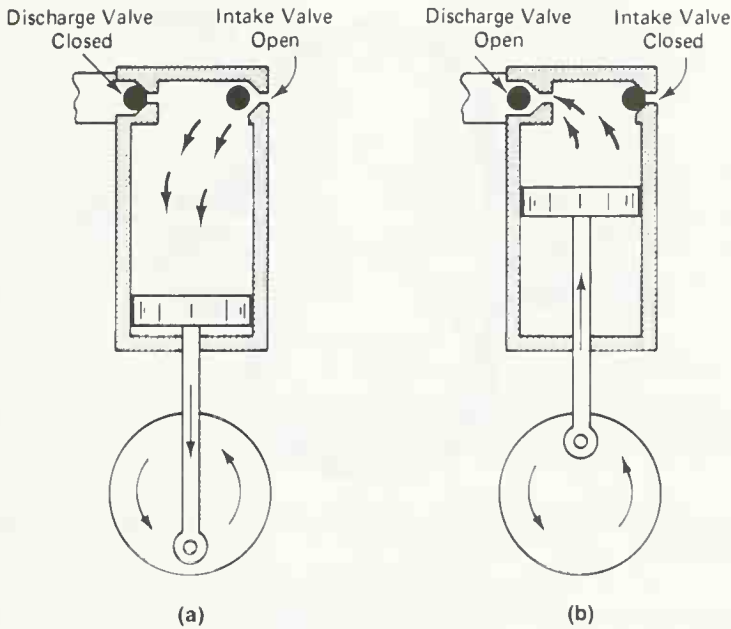
Figure 7–12.   Illustration of the operating of a reciprocating pump. (a) Intake stroke. (b) Pumping stroke.

For each revolution of the motor shaft, a reciprocating pump will make an intake and discharge stroke. This method is classified as a single-stage, single-acting pump. Piston area and chamber volume are the key factors in determining the potential output of this type of pump. In some situations two or more stages or cylinders may be driven by the same motor shaft.

Rotary-Gear Pumps.   The rotary-gear pump is another method of changing rotary motion into fluid power. Figure 7–13 shows the basic construction of an external type of rotary-gear pump. It contains two gears enclosed in a precision-machined housing. Rotary motion from the power source is applied to the drive gear. Rotation of this gear causes the second or driven gear to turn, with the teeth of the two gears meshing in the middle.

The basic operation of an external-gear rotary pump relies on unmeshed gears for carrying fluid away from the inlet side of the pump. Fluid trapped in these teeth is transferred around the periphery of both gears to the discharge side. When the gears remesh on the discharge side, fluid is forced to pass through the discharge port. Very little fluid
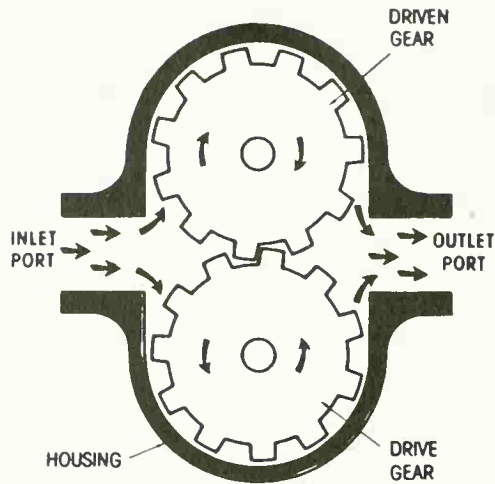
Figure 7–13.   Illustration of the basic construction of an external-gear type of rotary pump.

is permitted to return to the inlet side of the pump due to the close mesh structure of the gears.

Another type of rotary-gear pump uses internal gears (see Figure 7–14). In this type of pump one gear rotates within another gear. The inner gear (idler gear) is designed so that it has one or more fewer teeth than the driven outer gear (rotor gear). As the idler gear rotates within the rotor gear, the gear teeth unmesh at the inlet port and remesh at the discharge port. As the gears unmesh, fluid is drawn into the inlet port, filling the spaces between the gear teeth. The fluid moves smoothly around the head crescent and is expelled at the discharge port by the remeshing of the gear teeth. As a general rule, internal-gear rotary pumps can be operated equally well in either direction. The output capacity of this type of pump usually ranges from 0.5 to 1100 gallons per minute (gal/min).

Rotary-Vane Pumps.   Vane pumps also use rotary motion to circulate fluid or to compress air. This type of pump has a series of sliding vanes placed in slots around the inside structure of the rotor. As the rotor turns within its housing, centrifugal force or spring action forces the vanes out of the rotor. These vanes conform to the internal shape of the housing and capture volumes of fluid as they pass by the inlet port. Rotation of the rotor/vane unit quickly moves fluid from the inlet port to the outer port, thus increasing flow or compressing volume.

Figure 7–15 shows the basic construction of an unbalanced, straight-vane rotary pump. In this drawing the rotor is offset toward
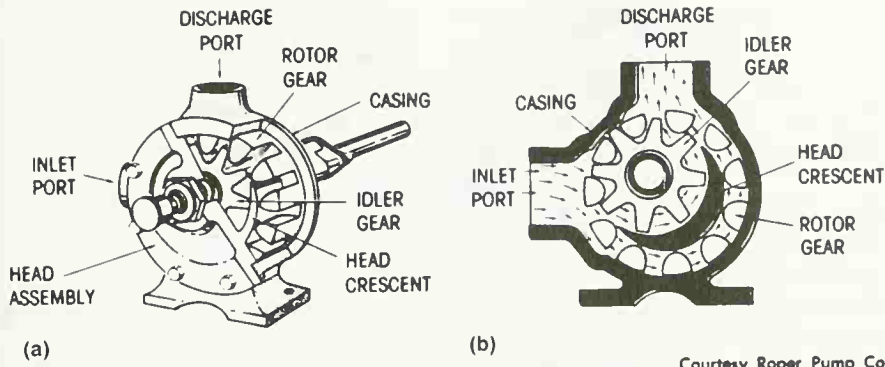
Figure 7–14.   Basic parts and principle of operation of an internal-gear type of rotary pump. **(a)** Cutaway view showing basic parts. **(b)** Principle of operation.
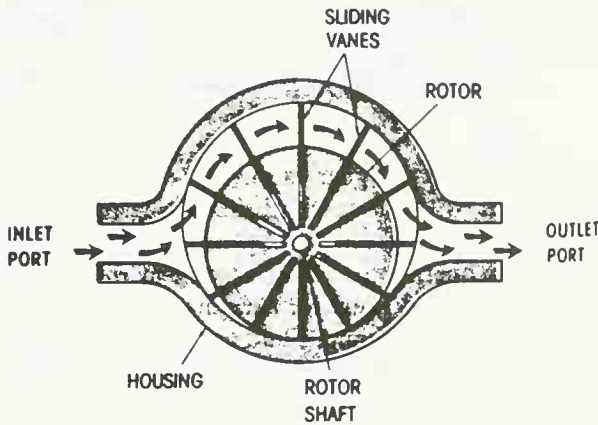
Figure 7–15.   Illustration of the basic construction of an unbalanced, straight-vane rotary pump.

the bottom of the housing. Through this type of construction, larger volume areas are present at the top of the rotor and small areas are present at the bottom. As a result, large volumes of oil or air can be made to move across the top with little or no return through the bottom. Offsetting the rotor in this way accounts for the unbalanced term commonly associated with this pump.

Balanced-vane pumps, by comparison, are designed so that the rotor is in the center of its housing. Large areas are made to appear at both the top and bottom of the housing. Separate inlet and outlet ports are developed by each side of the pump. Double pumping action of this

(a)

(b)
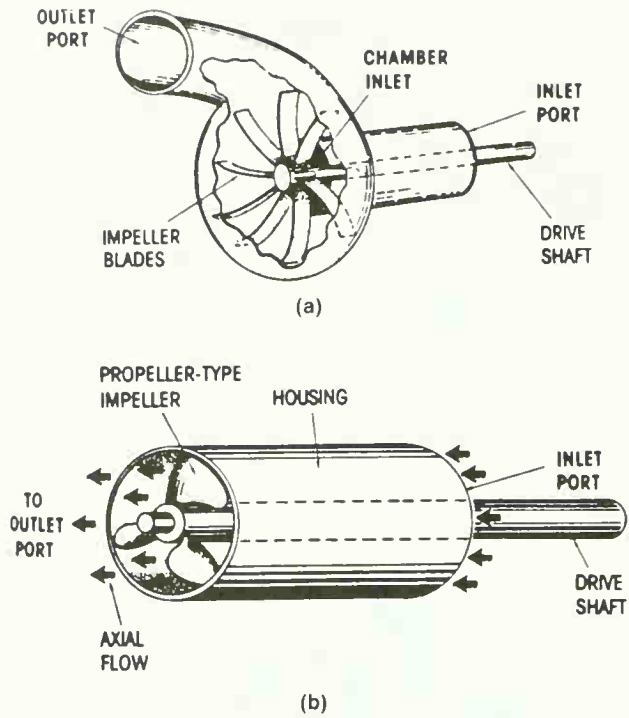
Figure 7–16.   Two types of centrifugal pumps. **(a)** Volute type. **(b)** Axial-flow type.

type develops a flow of air or oil that is smoother than the unbalanced type of pump.

Centrifugal Pumps.   A wide variety of centrifugal pumps are used today to circulate fluids. This type of pump is classified as having a nonpositive displacement of fluids. Pumps of this type are primarily used for low-pressure, high-volume flow applications in industry. Displacement of the fluid passing through a centrifugal pump is of an indeterminate amount compared with that of the other pumps discussed. The output of this pump is, therefore, dependent upon the rotational speed of its driving source.

In Figure 7–16 two distinct types of centrifugal pumps are illustrated. The pump of Figure 7–16A is commonly known as a *volute-type* pump because of the spiral (or volute) shape of its housing. When fluid enters the inlet port of the volute pump, it is set into rotation by the revolving blades of the impeller. This generates a centrifugal force which causes the fluid to move outward toward the inner wall of the housing.

The volute-shaped housing then causes the fluid to circulate in a spirallike path toward the outlet port. In order to keep the flow continuous, the inlet port must replace all fluid expelled from the outlet port.

In the axial-flow type of centrifugal pump illustrated in Figure 7–16B, the propeller-type blades of the impeller maintain fluid flow in the direction of the axis of rotation of the drive shaft.

The structure of a centrifugal pump is such that there is always some clearance between the driver blade and the housing. This means that the amount of fluid displaced by the outlet port is not directly or positively related to the input. The volume of fluid delivered to the output is, therefore, dependent upon the rotational speed of the pump and the resistance of the feed line connected to the outlet port. A build-up of resistance in the feed line may cause the fluid flow to slow down or even come to a complete stop. When this occurs, the operating efficiency of the pump drops to zero and no flow occurs. Any fluid in the pump simply rotates inside without being expelled. An increase in pump speed could be used to solve this problem. As a general rule, pumps of this type are only used for transferring large amounts of fluid at low pressure.

Fluid Conditioning Components

Fluid power systems employ a number of devices to condition air or hydraulic fluid before it is processed through the system. Typically, these devices are placed in the system to prolong component life by reducing the flow of foreign particles. The number of conditioning components used in a system depends upon the type of system. This ranges from a simple hydraulic system with a line filter or strainer to a rather sophisticated system that employs filters, strainers, and heat exchangers. Pneumatic systems, by comparison, condition air by filtering it to remove dirt and water, regulating the pressure to the proper level, and adding oil as a lubricant.

In *hydraulic fluid conditioning* the number of components, type of control devices, and condition of the operating environment are the major factors to consider in determining the amount of conditioning. For systems with manually operated control valves in a clean environment, a simple *intake strainer* may provide sufficient conditioning. For systems that operate for long hours in a dirty environment with precision control valves, *micrometer filters* and several strainers are considered a necessity.

Strainers are generally defined as coarse element devices placed in the pump inlet port or reservoir. These devices are usually of the stainless steel screen type with a wire mesh rating of 60 to 200 wires per

square inch. Strainers are frequently placed in the reservoir filler opening, air breather, and pump inlet feed line.

Filters provide a finer grade of fluid conditioning. Typically, these devices are made of some porous medium such as paper, felt, or fine wire mesh. Ratings range from 1 to 40 μm. A micrometer (μm) is one-millionth of a meter or 0.00003937 in. This rating refers to the particle size that is permitted to pass through the filter.

In-line and *T-type filters* are commonly used in hydraulic systems. The T-type filter has a removable bowl or shell for element replacement. This type of filter usually employs a bypass relief valve that goes into operation when the element becomes contaminated and restricts flow. In-line filters must be removed from the line to clean or replace the filter element. Bypass relief valves are optional with this type of filter, depending on its application.

Some hydraulic systems employ *heat-exchanger* units to maintain the temperature of the fluid at a desired level. Machinery that is operating near a furnace, or that is used in hot-metal areas, often requires heat-exchanger units to cool the hydraulic fluid. Forced-air fan units, water-jacket coolers, and gaseous cooling methods are often used to accomplish this function. As a general rule, applying heat is not a problem when a system becomes cold. It produces heat during its normal operation. Fluid heating is only required in portable systems during a cold starting condition.

In *pneumatic fluid conditioning* some devices that are different from hydraulic conditioning devices are used. Filtering, for example, must remove moisture as well as foreign particles from the air. In-line and T-type filters have special chemical filter elements made of a *desiccant*. This substance is very dry and is designed to attract moisture. Elements of this type often require periodic recharging, which is a heating process to dry the element. Some T-type filters also employ a moisture trap at the bottom of the bowl. If inspection of the glass bowl shows an accumulation of moisture, it should be cleared by the drain valve.

Pressure regulation is a necessary pneumatic conditioning process. After air passes through a T-type filter, it goes into a regulator valve. The movement of air passing through this valve can be changed by an adjustment screw. Through this adjustment it is possible to alter the system line pressure from the receiving tank to some desired operating level.

The *pressure regulators* of Figure 7–17 operate on a balance between atmospheric air pressure and system line pressure. Atmospheric pressure is applied to the top of the diaphragm through a vent. System pressure is applied to the bottom of the diaphragm. Turning the adjusting screw adds mechanical pressure to the atmospheric pressure applied to the top of the diaphragm. When this pressure is greater than
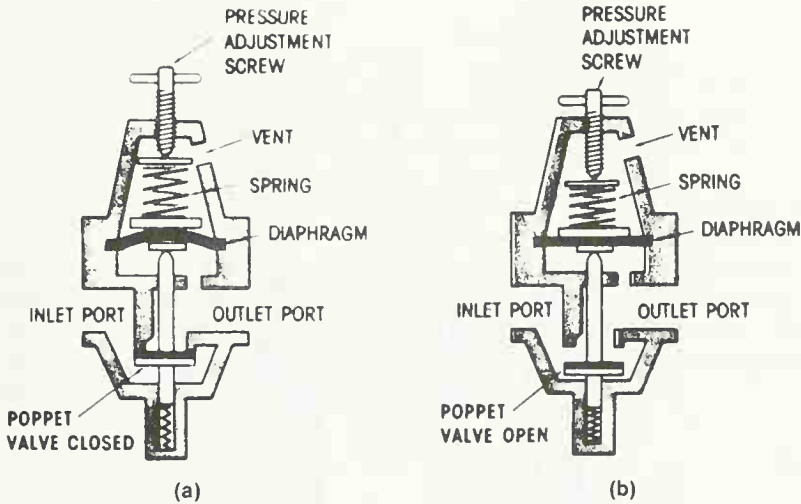
Figure 7–17.   Illustration of the operating principle of an air-pressure regulator valve. **(a)** System line pressure low. **(b)** System line pressure high.

the system pressure, the diaphragm is forced down. This action opens the poppet valve, which in turn admits more air from the receiving tank (see Figure 7–17A).

When the system line pressure becomes greater than the adjustment-screw/atmospheric-pressure setting, the diaphragm is forced upward. This action closes the poppet valve, thus maintaining the pressure at a set level. Figure 7–17B shows this condition of operation. Should the system line pressure drop, the process would repeat, thus maintaining an even level of line pressure.

A regulator is simply a pressure-balancing device that maintains system line pressure at a preset level. In order for this device to function properly, pressure from the receiving tank must be greater than the pressure setting of the regulator valve. To increase the line pressure, the adjusting screw must increase the spring pressure on the diaphragm. Loosening the adjustment screw lowers the line pressure by reducing the diaphragm pressure. Regulators may appear at several places in a pneumatic system.

Lubricators are unique conditioning devices found in pneumatic systems. This type of device simply adds a small quantity of oil to the air after it leaves the regulator. Through this conditioning process, valves and cylinders tend to last longer and operate more efficiently.

Figure 7–18 shows a typical lubricator that is used to supply a mist of oil to the transmission feed line of a pneumatic system. When air enters at the inlet port, it is directed into a narrowed area called the
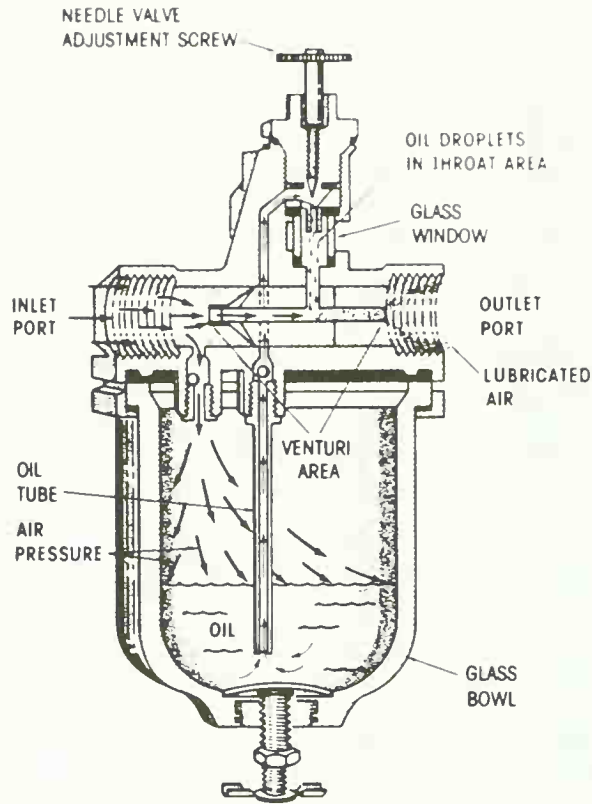
Figure 7–18. Illustration of the operating principle of a pneumatic lubricator unit.

venturi. While passing through this area, the flow increases in velocity. Pressure developed in the narrow venturi area is lower than that of the larger area. As a result of this condition, oil is forced from the glass bowl into the oil tube and transported to the top of the unit. The needle valve is then adjusted to regulate the oil flow so that small droplets fall into the throat area. The air velocity at the bottom of the throat causes these droplets to break into a fine mist of oil and mix with the passing air. Ultimately the lubricated air is forced to pass into the system through the outlet port. In pneumatic systems conditioning components such as the filter, regulator, and lubricator are often placed together in a combination unit, called an FRL unit.

Transmission Lines

The transmission lines of a fluid system may be either rigid metal tubing or a flexible thermosplastic hose. Rigid lines are used in applications that are usually free of vibration. As a general rule, rigid lines are more economical and provide less trouble than flexible lines.

Flexible transmission lines are made in a variety of types and sizes. The type of system and its application largely determine which transmission line is to be used. Three basic elements of a flexible hose are considered when selecting it for a specific application: the tube or inner lining, the reinforcement material, and the outside cover material. These considerations determine pressure limits, temperature operating range, and outside exposure resistance.

Fluid System Control

Control is essential for all fluid power systems. Fluid power can be made to do some type of useful mechanical work through proper control. Control is achieved by components that alter system pressure, direction, and volume of fluid flow.

Control devices are placed at several different places within a system. The actual location of a specific control is determined by the control function it must achieve. *Pressure regulators*, for example, may be attached to the output of the source or in the feed line attached to the load device. *Direction control* is typically found near the load device.

Pressure Control.   Pressure control refers to those operations that alter the pressure level of a fluid system. These include relief valves, reducing, bypassing, sequencing, and counterbalance. In hydraulic systems *pressure-relief valves* are used to dump the output of a positive displacement pump back into the reservoir when the pressure rises to a dangerous level. In this pressure control application the relief valve also serves as a safety control device.

In pneumatic systems pressure-relief valves are used to control smaller amounts of air. Excess air is not released into the atmosphere. The output port of a relief valve may be altered in size to achieve air pressure control.

Pressure control may also be used to establish operating sequences. Valves that achieve this type of control simply direct pressure in some predetermined sequence at certain pressure levels. Control of this type is achieved by a relief valve type of construction. When the main system pressure overcomes the valve setting, it shifts to a different port. Sequencing valves are often used in automated manufacturing systems.
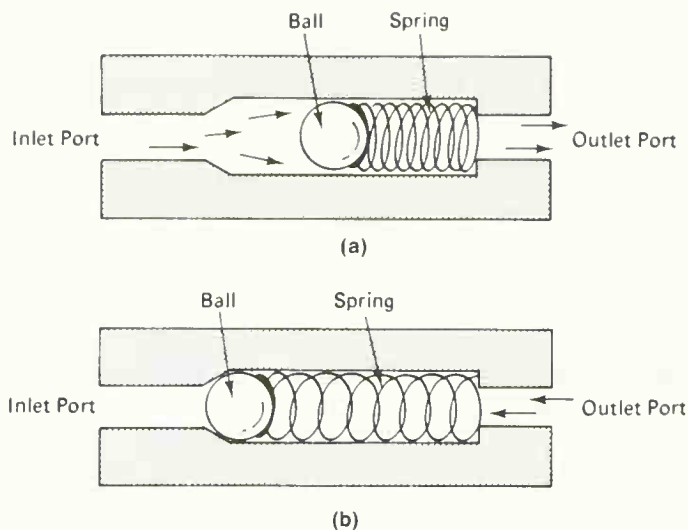
Figure 7–19.   Illustration of the operating of a check valve. **(a)** Free-flow condition. **(b)** Closed-flow condition.

Direction Control.   Directional control of fluid systems is achieved by devices designed to start, stop, or reverse fluid flow without causing an appreciable change in pressure or flow rate. One-, two-, three-, and four-way valves are some of the more common directional control devices. These devices may be actuated by pressure, mechanical energy, electricity, or by manual operation.

The control action of a directional valve can be achieved in a variety of different ways. One-way valves, for example, may operate on the seated-ball principle of the relief valve. One-way valves are commonly called *check valves*. This valve will permit flow in only one direction.

Figure 7–19 shows the operation of a check valve. When pressure is applied to the inlet port, it drives the ball away from its seat. When this occurs, the flow path becomes open and fluid passes through the valve. In the reverse direction, pressure forces the ball into its seat. This action prevents flow in this direction. Valves of this type are often used to permit free flow around some controls when the flow direction is reversed.

Two-way valves are simple directional control devices that have input and output connections placed in series with the transmission line. Valves of this type are designed to permit flow or shut it off. This type of control is achieved by placing gates, plugs, discs, spools, or other precision-machined objects in the line so that normal flow is obstructed. For example, a ball-type directional control valve has a ball that can be

rotated manually by an outside control handle. When the handle is in line with the feed line connections, flow occurs. Turning the handle 90° positions the ball to stop flow. This type of valve is used primarily for high-pressure control applications and is only one type of two-way control valve.

Three-way valves are designed primarily to permit the operator to shift to two different sources of pressure or to direct pressure to alternate devices. Generally, this type of valve is used to alter cylinder operation or to control hydraulic or pneumatic motors. Valves of this type can be actuated mechanically, manually, by pilot pressure, or by electricity. Basic designs include shifting spools, poppets, and shear seal plates. Figure 7–20 illustrates the structure of these basic types of three-way valves.

Figure 7–21 shows the basic operation of a spool-type, three-way directional control valve. When the manual control shaft is pushed toward the right, it causes the spools to shift right. Flow is through ports P and A. When the shaft is pulled to the left, the spools shift to the left. This permits flow through ports P and E or T. The port label P is a designation of pressure, A indicates actuating port, and E or T indicates exhaust or tank. These letter designations are assigned by the American National Standards Institute (ANSI).

As a general rule, three-way valves are designed for only two-position operation. Some valves have a neutral or off position. This additional position increases the control capabilities of the valve.

Four-way valves are used in control applications to start, stop, or reverse the direction of flow. In its simplest form, this type of valve has four working connections and is manufactured in two, three, four, five, and six different position combinations. Four-way valves are commonly used to control forward and reverse actuation of a double-acting cylinder or to reverse the rotational direction of a fluid motor.

Figure 7–22 shows the basic operation of a four-way, spool-type valve. In position 1 the pressure feed line is neutralized, or is in the off position. Position 2 shows the flow direction from P to A with an exhaust from B to E_2. Position 3 shows flow from P to B with the exhaust from A to E_1. With this type of control, flow direction can easily be reversed by manually shifting spool location. Actuation of this valve can be achieved mechanically, manually, electrically, or with a pilot pressure.

Flow Control.   Flow control is accomplished by components designed to alter the volume or flow rate of hydraulic or pneumatic systems. The rate at which air or hydraulic fluid is delivered to the load of a system determines its operational speed. Motor speed, for example, is directly dependent upon the flow rate of the applied fluid. By altering this rate, a motor can be made to operate at a wide variety of speeds.
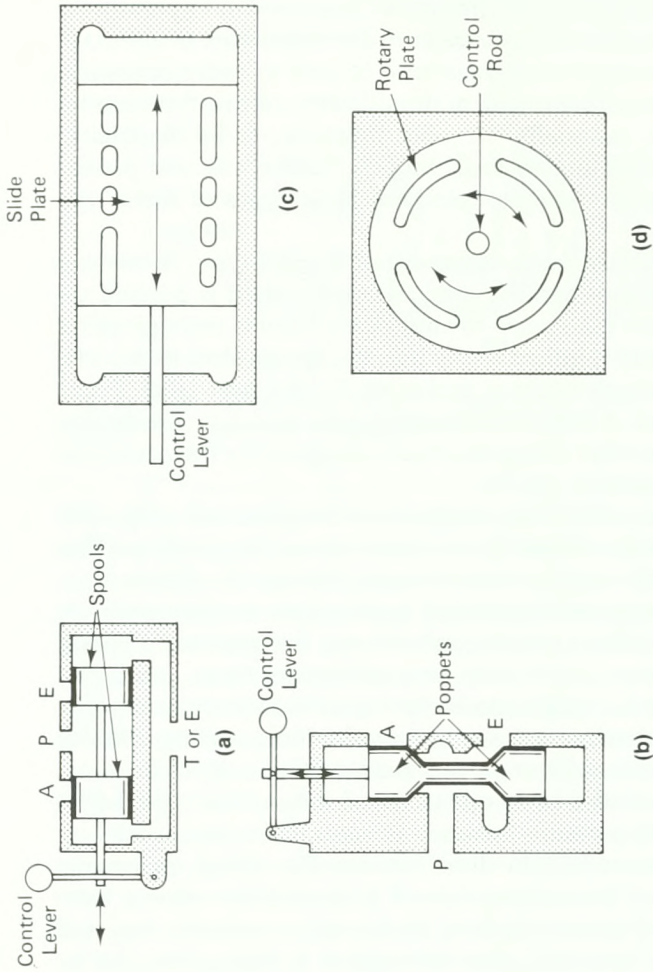
Figure 7-20. Illustration of the basic types of three-way valves. **(a)** Spool type. **(b)** Poppet type. **(c)** Sliding-plate, shear-seal type. **(d)** Rotary-plate, shear-seal type.

E OR T   A

SPOOLS

P

(a)

E OR T   A

SPOOLS

P

(b)
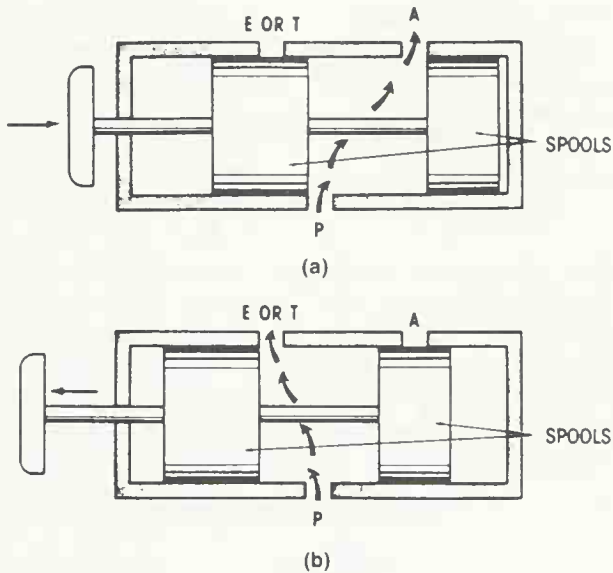
Figure 7–21.   Illustration of the operating principle of a spool-type, three-way valve. **(a)** Flow path with spools to the right. **(b)** Flow path with spools to the left.

Cylinder actuating speed is also controlled by fluid flow devices. To alter the linear motion of a cylinder, fluid may be controlled at the input feed line, the return line, or a combination of both. The term *metering* is often used to describe this function.

Figure 7–23 shows the operation of a flow control valve. Construction of this valve permits controlled flow from P to F. Flow level in this direction is adjusted by the needle valve. The letters P and F refer to the pressure and free-flow connections of the valve. Flow from F to P forces the ball of the check valve to move away from its seat, which produces uncontrolled flow. An arrow on the valve or ANSI symbol refers to the controlled flow direction.

Load Devices

The primary purpose of a fluid power system is to produce some form of useful work. The power output of a system refers to those parts that are designed to do some type of useful work. The term *load* is often used to describe this function. However, the term *actuator* is a more meaningful term when referring to specific components that produce a useful form of work in automated manufacturing operations.
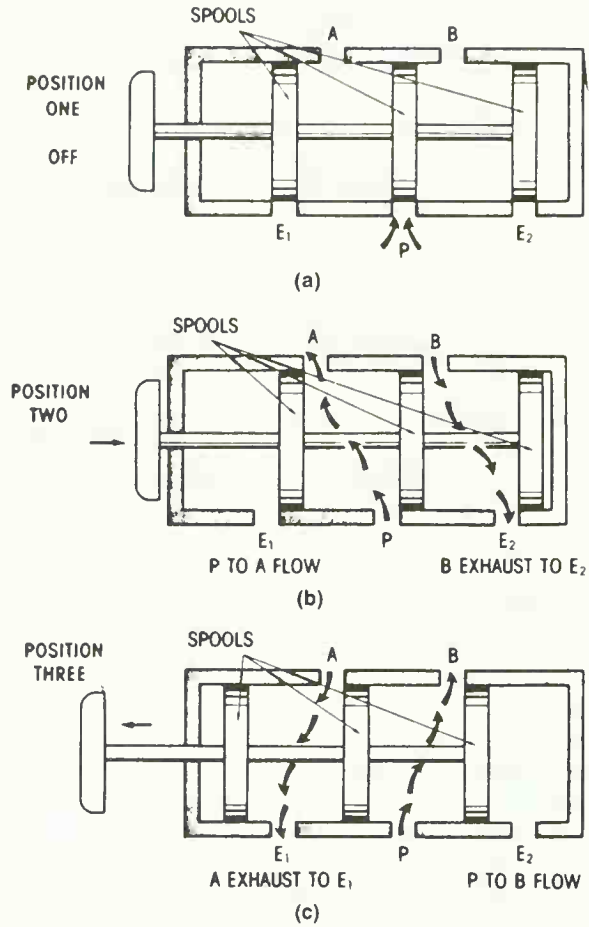
Figure 7–22. Illustration of the operating principle of a spool-type four-way valve. **(a)** Position 1. **(b)** Position 2. **(c)** Position 3.
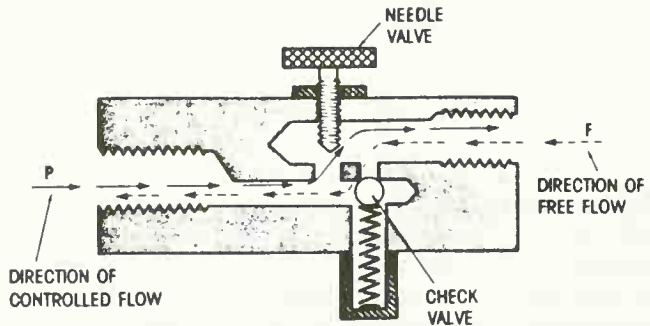
Figure 7–23. Illustration of the operating principle of a flow control valve.

    In industry fluid power systems are designed to produce work in the form of mechanical motion. Special actuators are used to produce either linear or rotary motion. Hydraulic and pneumatic systems produce linear motion through the action of a *cylinder* as the actuator. *Rotary actuators* are used to produce a twisting or turning motion to do certain types of work. The basic operating principles that apply to both hydraulic and pneumatic actuators are very similar.

Linear Actuators (Cylinders).   In industry *cylinders* are used to develop the force needed to lift, compress, hold, or position objects during automated manufacturing processes. In order to produce linear motion, hydraulic fluid or air is forced into a cylindrical chamber under pressure. A piston placed within the chamber is free to move due to the pressure applied to it. The area of the piston determines the amount of force it will develop from an applied pressure. The area of a round piston can be determined by the formula

$$A = \frac{\pi D^2}{4}$$

where

A = area of piston, in.^{2} or m^2

π = a constant (3.14)

D = diameter of piston, in. or m

The force developed by this piston may be determined by the formula

$$F = PA$$

where

F = force developed, lb or N

P = applied fluid pressure, lb/in.^{2} or Pa

A = area of piston, in.^{2} or m^2

    Single-acting cylinders have only one input port. Figure 7–24 shows the operation of a single-acting cylinder. When fluid is forced into the actuating port under pressure, it causes the piston to move. In this case weight is lifted by the fluid force driving the piston. The combined load of this system is the weight being lifted, the friction between the piston and cylinder walls, and the heat developed by fluid friction.
    Returning the piston to its original position can be achieved by first stopping the forward flow of fluid. A shutoff valve could achieve this
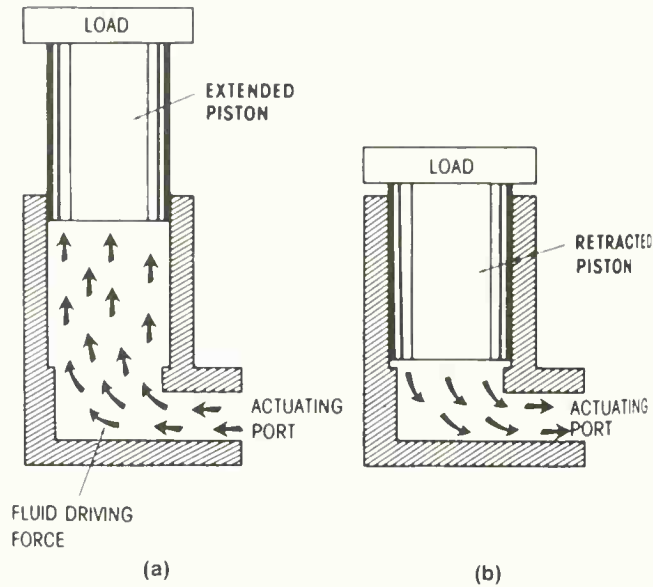
Figure 7–24.   Illustration of the operation of a single-acting cylinder. **(a)** Piston extended by fluid driving force. **(b)** Piston retracted by release of fluid driving force.

operation. Then the fluid under the piston must be released. The weight of the load would then cause the piston to retract when the fluid is released.

Double-acting cylinders, as the name implies, have power action in two directions. Two ports are needed with this type of cylinder. Fluid is applied to one port and expelled from the other port during its extending operation. Retracting the piston is achieved by reversing the fluid flow. A four-way valve is commonly used to control the motion of this cylinder. Industrial manufacturing applications include punch presses, rolling mills, machine-tool clamps, paper cutters, and actuators used with some types of industrial robots.

Figure 7–25 shows the basic operation of a double-acting cylinder. To initially extend the piston rod, fluid must be applied to the right side of the piston and removed from the left side. This action would force the piston to move to the left. Switching the fluid flow would cause the piston to move to the right. As a general rule, the retracting force is somewhat less than the extending force. The area of the piston in this case is somewhat smaller due to the connection of the piston rod.

The double-acting cylinder just discussed is of the differential type. The linear action of the piston is determined by the pressure difference on each side of the piston. The piston rod extends only from one side

(a)

(b)
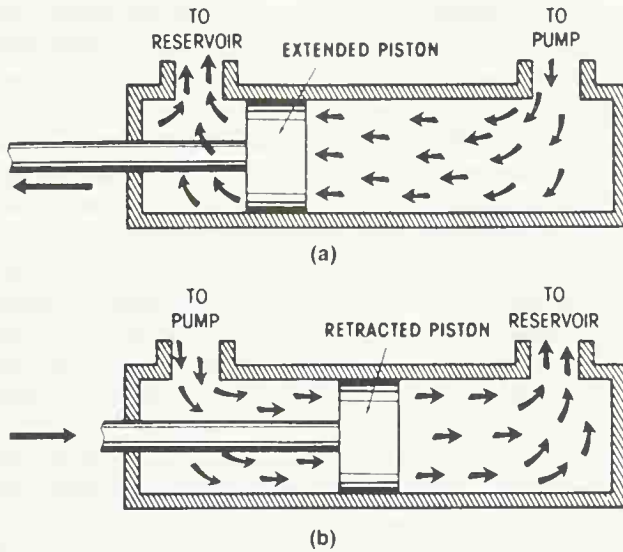
Figure 7–25. Illustration of the operation of a double-acting cylinder. **(a)** Fluid driving piston to the left. **(b)** Fluid retracting piston to the right.

of the cylinder. A nondifferential type of cylinder has rods extending from both ends of the piston. Cylinders of this type can provide an equal force in either direction.

Rotary Actuators.   *Rotary actuators* are fluid power devices designed to produce a limited amount of rotary motion in either direction. Figure 7–26 illustrates two of the most common types. Fluid applied to port *A* causes the rotor to move in a clockwise direction a certain distance.

(a)   (b)
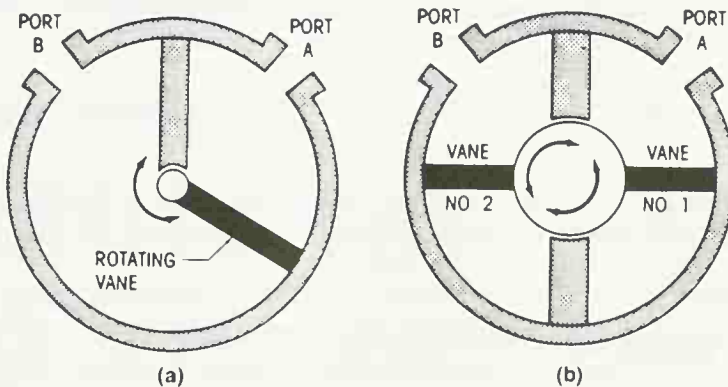
Figure 7–26.   Rotary actuators. **(a)** Single-vane type. **(b)** Double-vane type.

Counter-clockwise rotation is achieved by applying fluid to port *B* and expelling fluid from port *A*. The single-vane rotor can be made to turn approximately 280° in either direction. The double-vane rotor has twice the turning power but can only turn approximately 100° in either direction. Actuators of this type are used to lift or lower, to open or close, and in indexing operations. Rotary actuators are commonly used in continuous reciprocating operations such as that of a punch press.

Fluid Motors.   Fluid motors are designed to convert the force of a moving fluid into rotary motion. Fluid motors and pumps are generally very similar in appearance and operation. In a fluid motor the power of a moving fluid is used to produce rotary motion by driving vanes, gears, or pistons. The pump, of course, must be driven by a rotary force to produce fluid flow.

Gear pumps can be used interchangeably as motors. Gear motors are capable of operating at speeds up to 5000 rpm. Both internal and external gear motors are currently available.

Fluid motors are generally classified according to the type of fluid displacement they possess. Gear, vane, and piston motors usually have a fixed displacement characteristic. This type of motor accepts a certain amount of fluid and moves it with each revolution. The operating speed of the motor depends entirely on the amount of fluid supplied by the source. Variable displacement motors, by comparison, are designed so that the amount of fluid circulated during each revolution can be changed. The piston type of motor fits into this classification. The length of its stroke is altered to produce the variable displacement characteristic. The speed of this motor can, therefore, be changed by an outside adjustment. Operating speeds of up to 3000 rpm are typical.

The rotary motion produced by a fluid motor is a form of power intended to do work. Its turning capability is a measure of torque, which is equal to the developed force multiplied by the radius of the rotating arm. Mathematically this is expressed by the formula

$$\text{Torque} = \frac{\text{pressure (lb/in.}^2) \times \text{displacement (in.}^3)/\text{revolution}}{2} \quad \text{in.-lb}$$

The output power developed by a fluid motor is commonly expressed as horsepower. Mathematically, horsepower can be determined by the formula

$$\text{Horsepower} = \frac{\text{torque (in.-lb)} \times \text{speed (rpm)} \times 2}{33,000 \text{ ft-lb/min}} \quad \text{hp}$$

Motor performance information supplied by the manufacturer can normally be obtained to make these calculations for manufacturing applications.

Indicators.   The most significant measurement to be made in a fluid system is pressure. Indicators that measure pressure play a very important role in the overall performance of a system. Regulators and pneumatic receiver tanks often employ pressure indicators or gauges as permanent fixtures. A wide range of pressures must be measured. Negative pressures (vacuums) as low as 0.00002 lb/in.^{2} up to positive pressures as high as 1×10^6 lb/in.^{2} must be measured in automated industrial equipment. This wide range of measurement requires a number of different indicating devices.

In addition to pressure, fluid systems often require measurements of flow and temperature. Indicators that measure and display these values are very valuable methods used to analyze system operating efficiency. Temperature and flow indicators are rarely attached to the system as a permanent fixture. They are, however, used periodically to test and evaluate a fluid system during operation.

Pressure indicators employ an element that physically changes shape when different values of pressure are applied. Spiral and helix coil elements have a tendency to uncoil when pressure is applied. The *Bourdon tube* element tends to straighten when pressure is applied to it. The physical change produced by these different elements can then be used to move an indicator hand on a scale or a stylus on a paper chart.

Flow indicators are primarily used to test flow rates from pumps, at key locations, and at the inlet and outlet ports of actuators. By monitoring flow rates, it is possible to determine system efficiency and to minimize maintenance problems. Measurements of this type are conveniently divided into three general categories: the differential pressure method, the force method, and the velocity flow method.

REVIEW QUESTIONS

1.   What are some industrial applications of hydraulic systems?
2.   What are some industrial applications of pneumatic systems?
3.   What are the basic parts of a fluid power system?
4.   Discuss Pascal's law and its application in fluid power systems.
5.   Define the terms (a) *force*, (b) *pressure*, (c) *work*, and (d) *power*.
6.   How is power transferred in a fluid power system?

7. Give the function of each of the following parts of a hydraulic system: (a) motor, (b) pump, (c) pressure relief valve, (d) gauge, and (e) reservoir.

8. What are some types of fluid pumps? Give a brief description of each.

9. What is the purpose of the fluid conditioning components of a fluid power system?

10. Discuss the operation of a pressure regulator.

11. What are some types of control devices used with fluid power systems?

12. How is direction control of a fluid power system accomplished?

13. What is a single-acting cylinder? Double-acting cylinder?

14. How is the torque developed by the motor of a fluid power system determined?

15. What are some types of indicators used with fluid power systems?

ELECTRICAL MACHINERY AND POWER SYSTEMS

The operation of automated manufacturing systems and industrial robots relies upon various types of electrical machinery. Electrical power systems are depended upon to supply energy to manufacturing equipment so that industrial operations and processes may be performed. A robotic system is a unique type of automated manufacturing system. These systems sometimes require several types of energy inputs and specialized machinery for proper operation.

This chapter provides an overview of the types of electrical machinery and power systems which may be utilized with robotic systems. The operation of the electrical machinery used with robotic systems is dependent upon the proper distribution and control of electrical power. Robotic systems use both ac and dc electrical energy inputs.

Brief Overview of Electrical Energy Sources

Industries use over 40 percent of the electrical energy produced in the United States. Sources of electrical energy, therefore, are very important for automated industrial processes. Without sources of electrical energy, industries could not continue to produce the goods and services upon which we have become so dependent. It is important for those involved

with industrial operation to be familiar with electrical energy sources. A knowledge of how electrical energy is produced and the sources of energy available are fundamental to industrial system operation. Industry depends on electrical energy for heat, light, machine operation, electrochemical processes, and other automated processes. In addition, many industries produce electrical equipment and appliances and, therefore, depend on electrical energy for their product marketing.

There are several methods presently used to produce electrical energy. The most frequently used methods in the United States are *fossil fuel* (coal, oil, and gas) systems, *hydroelectric* systems, and *nuclear fission* systems. In addition, various other methods, some of which are in the experimental stages, may be used as future energy sources. Such systems as solar cells, geothermal systems, wind-powered systems, magnetohydrodynamic (MHD) systems, nuclear fusion, and fuel cells are being considered.

Coal-fired electrical energy sources produce nearly one-half of the electrical power used in the United States. Natural gas-fired systems are used to produce about one-fourth of our electrical power, while oil-fired systems produce over 10 percent. The relative contribution of each system to the total electrical power produced in the United States is subject to rapid change due to the addition of new power generation facilities and fuel availability. At the present time, over 80 percent of our electrical energy is produced by fossil fuel systems.

The energy from stored water is also used to generate electrical energy. This method of energy conversion is used in *hydroelectric* power systems. Water is channeled through a control gate and passes through the blades of a reaction-type turbine, which produces rotation. This mechanical energy is used to rotate a generator that is connected directly to the turbine shaft. Rotation of the alternator then causes electrical energy to be produced.

Some of our electrical energy is now produced by nuclear fission power plants. The process is somewhat similar to fossil fuel power systems. Heat produced by a reaction in a nuclear reactor is used to produce steam to drive a steam turbine. The steam turbine provides mechanical energy to rotate an electrical generator.

Electrical energy produced at power plants is alternating current. This electrical energy is then transmitted by means of long-distance overhead power lines to industries, residences, and commercial buildings. Once this ac electrical energy is distributed to an industry, the interior distribution and control system of the building supplies the proper electrical energy to the equipment which is used throughout the building.

The ac electrical energy requirement for an automated manufacturing system may be either three-phase or single-phase. For larger machines three-phase alternating current is ordinarily used. Several machines used for automated manufacturing require dc power supplies.

Industries use dc sources for many specialized processes. Electroplating and dc variable-speed motor drives are two examples that show the need for dc energy to sustain industrial operations. Many robotic systems use dc servo motors and controls. Although most of the electrical power produced in the United States is three-phase alternating current, several methods are available to convert alternating current to direct current for industrial use. Direct current is also made available through primary and secondary chemical cells, which are used extensively. The process of converting alternating current to direct current is called *rectification*. Rectification systems are usually the most convenient and inexpensive methods of providing dc energy to industrial equipment.

Electric Motors

Electric motors convert electrical energy into mechanical energy. There are many types of motors used in industries. In fact, the motor load is, for many industries, the major power-consuming equipment. Motors of various sizes are used for processes ranging from precise machinery control to the movement of massive pieces of equipment. Robotic systems ordinarily use several motors.

All motors, regardless of whether they operate from an ac or a dc power source, have several basic characteristics in common. Their basic parts include (1) a *stator*, which is the frame and other stationary components; (2) a *rotor*, which is the rotating shaft and its associated parts; and (3) auxiliary equipment such as a brush-commutator assembly for dc motors and a starting circuit for single-phase ac motors. The basic parts of a dc motor are shown in Figure 8–1. The function of a motor is to produce mechanical energy in the form of rotary motion. To produce rotary motion, a motor must have an electrical energy input. Motion is produced in a motor due to the interaction of a magnetic field and a set of conductors.

The rotating effect produced by the interaction of two magnetic fields is called *torque*. The torque produced by a motor depends on the strength of the machine's magnetic field and the amount of current flowing through its conductors. As the magnetic field strength or the current through the conductors increases, the amount of torque or rotary motion will also increase.

dc Motors

Motors that operate from dc power sources are used in industry when speed control is desirable. Direct current motors are classified as series, shunt, or compound machines, depending on the method of connecting
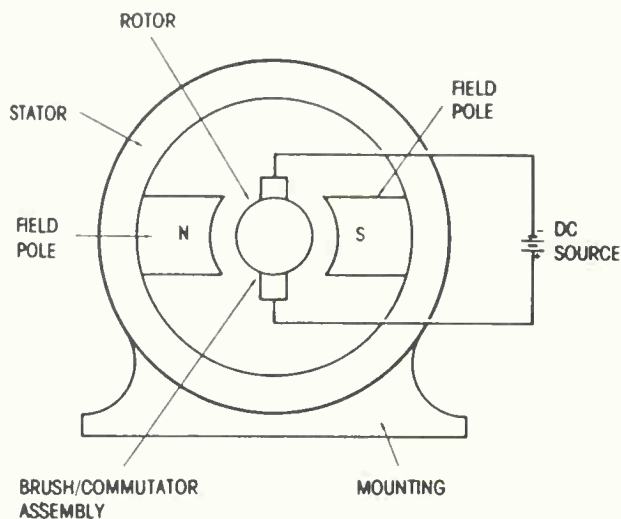
Figure 8–1.   Basic parts of a dc motor.

the rotor and stator windings of the machine. Also, permanent-magnet dc motors are used for certain applications in industries.

The operational characteristics of dc motors can be generalized by referring to Figure 8–2. Most electric motors exhibit characteristics similar to those shown in the block diagram. When discussing dc motor characteristics, one should be familiar with the following terms: load, speed, counterelectromotive force (cemf), armature current, and torque. The amount of mechanical load applied to the shaft of a motor determines its operational characteristics. As the mechanical load is increased, the speed of a motor tends to decrease. As the speed decreases, the voltage produced in the conductors of the motor due to generator action (cemf) decreases. The generated voltage, or cemf, depends upon the number of rotating conductors and the speed of rotation. Therefore, as the speed of rotation decreases, so does the cemf.

The cemf generated by a motor is in opposition to the supply voltage. Since the cemf is in opposition to the supply voltage, the actual working voltage of a motor will increase as the cemf decreases. When the working voltage increases, more current will flow through the rotor windings. The torque of a motor is directly proportional to the rotor current. Thus, torque will increase as rotor current increases.

To briefly discuss the opposite situation, if the mechanical load connected to the shaft of a motor decreases, the speed of the motor tends to increase. An increase in speed causes an increase in the cemf. The cemf is in opposition to the supply voltage. As the cemf increases, the rotor current decreases. A decrease in rotor current causes a decrease in torque.
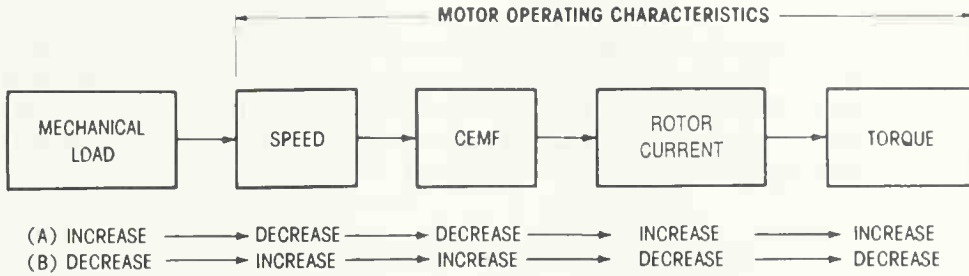
Figure 8–2. Operational characteristics of dc motors.

Torque varies with changes in load. Each of the steps involved should be considered to understand dc motor operation. As the load on a motor is increased, its torque also increases to try to meet the increased load requirement. However, the current drawn by a motor from the power source also increases when the load is increased.

The presence of a cemf to oppose the armature current is very important in motor operation. The lack of any cemf when a motor is being started explains why motors draw a very large initial starting current as compared to their running current when full speed is reached. Maximum armature current flows when there is no cemf. As the cemf increases, the rotor current decreases. Thus, resistances in series with the rotor circuit are often used to compensate for the lack of cemf and to reduce the starting current of a motor. After the motor has reached full speed, these resistances are bypassed by automatic or manual switching systems in order to allow the motor to produce maximum torque.

The horsepower rating of a motor is based on the amount of torque produced at the rated full-load values. Horsepower, which is the usual method of rating motors, can be expressed mathematically as

$$\text{hp} = \frac{2\pi ST}{33,000}$$

$$= \frac{ST}{5252}$$

where

hp = horsepower rating

2π = a constant

S = speed of motor, rpm

T = torque developed by motor, ft-lb

The most desirable characteristic of dc motors is their speed control capability. By varying the applied dc voltage, speed can be varied from zero to the maximum rpm of the motor. Some types of dc motors have more desirable speed characteristics than others. For this reason, we can determine the comparative speed regulation for different types of motors. Speed regulation is expressed as

$$\text{Percent of speed regulation} = \frac{S_{nl} - S_{fl}}{S_{fl}} \times 100$$

where

$$S_{nl} = \text{no-load speed, rpm}$$

$$S_{fl} = \text{rated full-load speed, rpm}$$

Good speed regulation (low percentage) results when a motor has nearly constant speeds under varying load situations.

The types of dc motors commercially available fall basically into four categories: (1) permanent-magnet, (2) series-wound, (3) shunt-wound, and (4) compound-wound dc motors. Each of these motors has different characteristics due to its basic circuit arrangement and physical properties.

Permanent-Magnet dc Motor.   The permanent-magnet dc motor is illustrated in Figure 8–3. The permanent-magnet motor is ordinarily used where a low amount of torque is required. When this type of motor is used, the dc power supply is connected directly to the rotor conductors through the brush-commutator assembly. The magnetic field is produced by permanent magnets mounted to the stator.

Series-Wound dc Motor.   The manner in which the rotor and stator circuits of a dc motor are connected determines its basic characteristics. Each of the types of dc motors are similar in construction.

The series-wound motor illustrated in Figure 8–4 has the armature (rotor) and field circuits connected in a series arrangement. There is only one path for current to flow from the dc voltage source. Therefore, the field has a low resistance. Changes in load applied to the motor shaft cause changes in the current through the field. If the mechanical load increases, the current also increases. The increased current creates a stronger magnetic field. The speed of a series motor varies from very fast at no load, to very slow at heavy loads. Since large currents may flow through the low resistance field, the series motor produces a high torque. Series motors are used where heavy loads must be moved and speed regulation is not important.

PERMANENT-MAGNET
POLES

PICTORIAL   SCHEMATIC
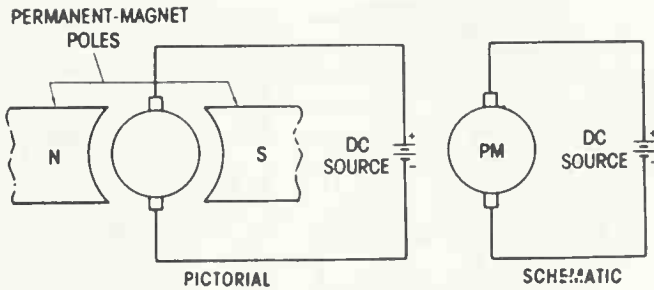
Figure 8-3. Permanent-magnet dc motor.

LOW-RESISTANCE
FIELD WINDINGS

FIELD

ARMATURE

DC SOURCE

SCHEMATIC

DC SOURCE

PICTORIAL
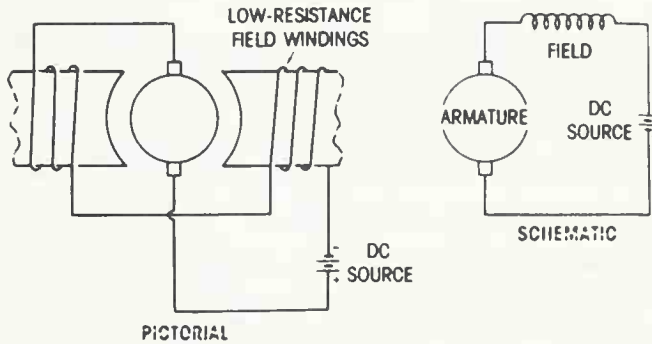
Figure 8-4. Series-wound dc motor.

Shunt-Wound dc Motors. Shunt-wound dc motors are more commonly used than any other type of dc motor. As shown in Figure 8-5, the shunt-wound dc motor has the field coils connected in parallel with the armature (rotor). This type of dc motor has field coils that have relatively high resistance. Since the field is a high-resistance parallel path, a small amount of current flows through the field.

Most of the current drawn by the shunt motor flows in the armature circuit. Since the armature current has little effect on the strength of the field, motor speed is not affected appreciably by variations in load current. The field current, however, can be varied by placing a variable resistance in series with the field windings. Since the current in the field circuit is low, a low-wattage rheostat can be used to vary the speed of the motor. As the field resistance increases, the field current decreases. A decrease in field current reduces the strength of the electromagnetic field. When the field flux is decreased, the armature will rotate faster.

HIGH-RESISTANCE
FIELD WINDINGS

PICTORIAL   SCHEMATIC
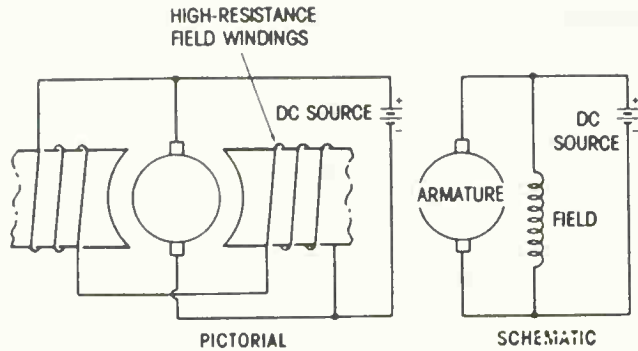
Figure 8–5.   Shunt-wound dc motor.

Thus, the speed of a dc shunt motor can easily be varied by using a field rheostat. The shunt-wound dc motor has very good speed regulation. Because of its good speed regulation and its ease of speed control, the shunt-wound dc motor is commonly used for industrial applications. Many types of variable-speed machine tools are driven by shunt-wound dc motors.

Compound-Wound dc Motors.   The compound-wound dc motor has two sets of field windings, one in series with the armature and one in parallel. (See Figure 8–6.) This motor combines the desirable characteristics of the series- and shunt-wound motors. It has high torque, similar to a series-wound motor, and good speed regulation, similar to a shunt-wound motor. Therefore, when good torque and good speed regulation are needed for an industrial application, the compound-wound dc motor can be used. However, compound-wound motors are more expensive.

Single-Phase, ac Motors

Single-phase ac motors are common for industrial as well as commercial and residential usage. They operate from a single-phase ac power source. There are three basic types of single-phase ac motors: universal motors, induction motors, and synchronous motors.

Universal Motors.   Universal motors can be powered by either ac or dc power sources. The universal motor illustrated in Figure 8–7 is constructed in the same way as a series-wound dc motor; however, it is designed to operate with either alternating current or direct current. The series-wound motor is the only type of dc motor that will also operate with ac power applied. The universal motor is one type of ac motor that

HIGH-RESISTANCE, SHUNT-FIELD WINDINGS

LOW-RESISTANCE, SERIES-FIELD WINDINGS

DC SOURCE

PICTORIAL

SERIES FIELD

ARMATURE   SHUNT FIELD   DC SOURCE

LONG SHUNT

SERIES FIELD

ARMATURE   SHUNT FIELD   DC SOURCE

SHORT SHUNT
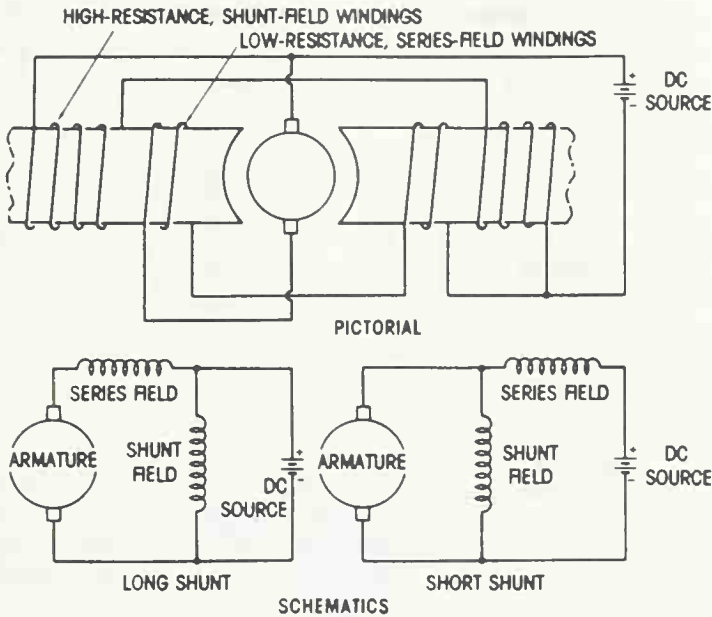
SCHEMATICS

Figure 8–6.   Compound-wound dc motor.

FIELD WINDINGS

ARMATURE

TO AC OR DC POWER SOURCE

(a)

WOUND ARMATURE WITH BRUSH SPLIT-RING COMMUTATOR ASSEMBLY

CONCENTRATED (SALIENT) FIELD WINDINGS

TO AC OR DC POWER SOURCE

(b)
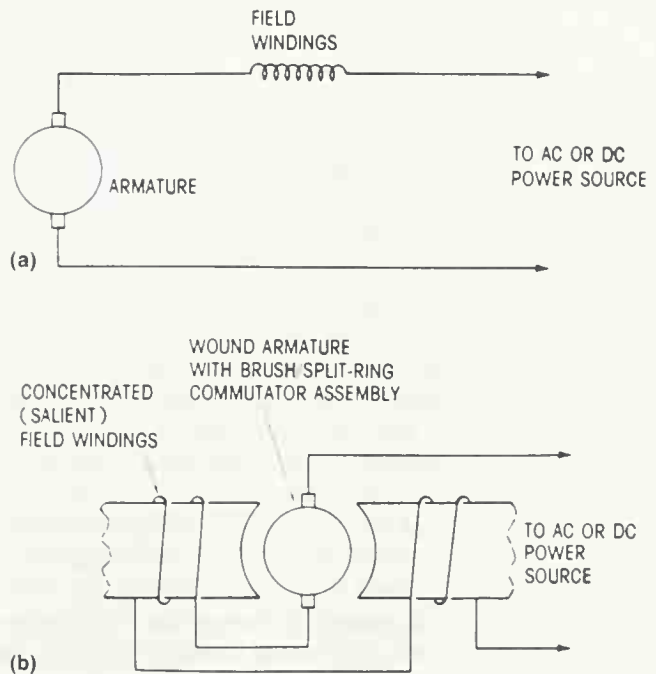
Figure 8–7.   Universal motor. (a) Pictorial diagram. (b) Schematic diagram.

STATOR WINDINGS   SQUIRREL-CAGE ROTOR

N
INSTANTANEOUS
POLARITY

S

CIRCULAR
CONNECTING PLATES

SHAFT

COPPER CONDUCTORS
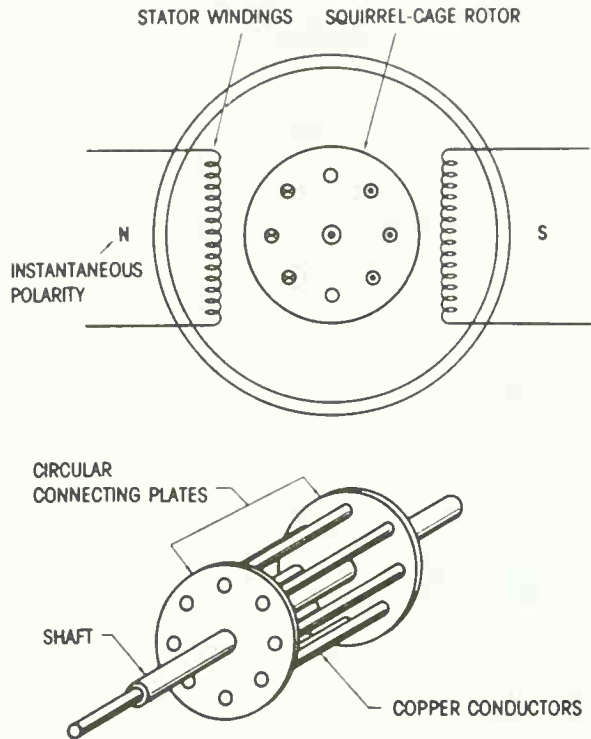
Figure 8–8.   Squirrel cage rotor.

has concentrated field windings. These field windings are similar to those of dc motors. The speed and torque characteristics of universal motors are similar to dc series-wound motors. Applications of universal motors in industry are mainly for portable tools and small motor-driven equipment.

Induction Motors.   Induction motors have a solid rotor, referred to as a squirrel cage rotor and shown in Figure 8–8. They have large-diameter copper conductors soldered at each end to a circular connecting plate. When current flows in the stator windings, a current is induced in the rotor. The stator polarity changes in step with the applied ac frequency. This develops a rotating or revolving magnetic field around the stator. The rotor becomes instantaneously polarized due to the current flow through the copper conductors. The rotor will therefore tend to rotate in step with the revolving magnetic field of the stator. Some method of initially starting the rotation must be used so that the rotor will rotate. However, due to inertia, a rotor must be initially put into motion by some auxiliary starting method.

The speed of an ac induction motor is based on the speed of the rotating magnetic field and the number of stator poles that the motor has. The speed of the rotating stator field can be expressed as

$$S = \frac{f \times 120}{n}$$

where

S = speed of rotating stator field, rpm
f = frequency of applied ac voltage, H
n = number of poles in stator windings
120 = conversion constant

A two-pole motor operating from a 60-Hz source would have a stator speed of 3600 rpm. The stator speed is also referred to as the *synchronous speed* of a motor. For 60-Hz operation, the following synchronous speeds would be obtained:

1. Two-pole, 3600 rpm;
2. Four-pole, 1800 rpm;
3. Six-pole, 1200 rpm;
4. Eight-pole, 900 rpm;
5. Ten-pole, 720 rpm; and
6. Twelve-pole, 600 rpm.

The difference between the revolving stator speed of an ac induction motor and the rotor speed is called *slip*. The rotor speed is somewhat less than the revolving stator speed in order to develop torque. The more the rotor speed lags behind the stator field, the more torque is developed. Slip is expressed mathematically as

$$\text{Percent slip} = \frac{S_s - S_r}{S_s} \times 100$$

where

S_s = synchronous (stator) speed, rpm
S_r = rotor speed, rpm

As the rotor speed becomes closer to the stator speed, the percentage of slip becomes smaller.

Three-Phase ac Motors

Three-phase ac motors are often called the "work-horses of industry." Most motors used in industry are operated from three-phase ac power sources. There are two basic types of three-phase motors: (1) three-phase induction motors and (2) three-phase synchronous motors.

Induction Motors.   The three-phase induction motor has a squirrel cage rotor. Since three-phase voltage is applied to the stator, no external starting mechanisms are needed. Three-phase induction motors are made in a variety of integral horsepower sizes and have good starting and running torque characteristics. A three-phase induction motor is shown in Figure 8–9.

Three-phase induction motors are used for many industrial applications, such as mechanical energy sources for machine tools, pumps, elevators, hoists, conveyors, and many other automated systems.

Synchronous Motors.   Three-phase synchronous motors are unique and very specialized motors. They are considered constant-speed motors and can be used to "correct power factors" of three-phase systems. Direct

NOTE: Stator windings may be connected in either a wye or a delta configuration
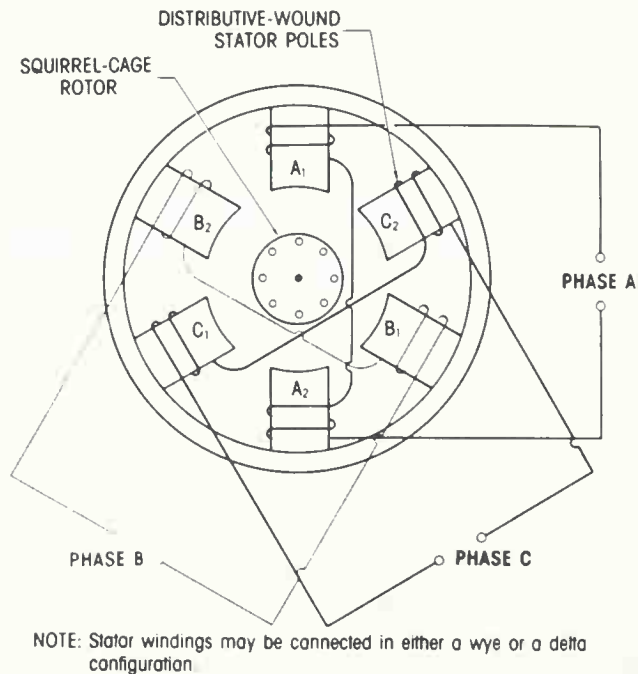
Figure 8–9.   Three-phase ac induction motor.

current is applied to the rotor to produce electromagnetic field, and the stator has windings. Three-phase ac power is applied to the stator.

The three-phase synchronous motor differs from the three-phase induction motor in that the rotor is wound and is connected through a commutator-brush assembly to a dc power source. Three-phase synchronous motors, in their pure form, have no starting torque. Some external means must be used to initially start the motor. Synchronous motors are constructed so that they will rotate at the same speed as the revolving stator field. At synchronous speed, rotor speed equals stator speed and the motor has zero slip.

Rotary Electric Actuators

In industry today there is a need for devices that produce a type of rotary motion that is somewhat different from that produced by an electric motor. This type of actuator employs rotary motion to control the angular position of a shaft. Synchro systems and servomechanisms are used in industry to achieve this basic operation. Through these devices it becomes possible to transmit rotary motion between locations without direct mechanical linkage. Robotic systems ordinarily use rotary actuators.

Synchro systems are motor-generator units connected together to allow the transmission of angular shaft positions by electromagnetic field changes (see Figure 8–10). When an operator turns the generator shaft of the unit to a certain position, it automatically rotates the motor shaft to an equivalent position at a remote location. With this type of system it is possible to achieve accurate control over great distances.

Servomechanisms are employed in synchro systems that require increased torque or precise movements of a control device. A *servome-*
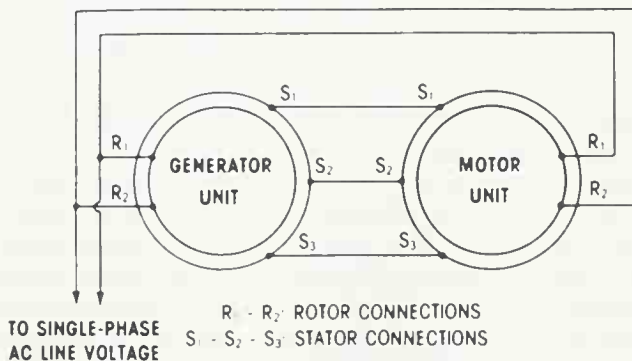
Figure 8–10.   Circuit diagram of a basic synchro system.

chanism is ordinarily a special type of ac or dc motor that drives a precision piece of equipment in specific angular increments. Systems that include servomechanisms generally require amplifiers and error-detecting devices to control angular displacement of a shaft.

Synchro Systems.   A synchro system has two or more devices that are similar in appearance to small electric motors. These devices are connected together in such a way that the angular position of the generator shaft can easily be transmitted to the motor or receiver unit. Figure 8–10 shows a schematic diagram of a basic synchro unit. As a general rule, the generator and motor units are identical electrically. Physically, the motor unit has a metal flywheel attached to its shaft to prevent shaft oscillations or vibrations when it is powered. The letters *G* and *M* inside the electrical symbol denote the generator or motor functions.

Single-phase ac voltage is used to power the system of Figure 8–10. The voltage is applied to the rotors of both the generator and motor. The stator windings are connected together as indicated. When power is applied to the system, the motor will position itself according to the location of the generator shaft. No change will take place after the motor unit aligns itself with the generator position. Both units will remain in a stationary condition until some further action takes place. Turning the generator shaft a certain number of degrees in a clockwise direction will cause a corresponding change in the motor unit. If calibrated dials were attached to the shaft of each unit, they would show the same angular displacement.

Any change in rotor position of the generator unit is translated into a voltage change and applied to the motor stator coils. Through this action, linear displacement changes can be transmitted to the motor through the stator coils. Systems of this type are used in industrial automatic process control applications.

Servo Systems.   Servo systems are specific types of electrical machines concerned with such things as changing the mechanical position or speed of an object. Mechanical position applications include numerical control machinery, process control indicating equipment, and robotic systems. Speed applications are found in conveyor belt control units, spindle speed control in machine tool operations, and disk or magnetic tape drives for computers. As a general rule, a servo system is a rather complex unit that follows the commands of a closed-loop control path. Figure 8–11 shows the components of a typical servo system.

The input of a servo system serves as the reference source or as a set point to which the load element responds. By changing the input in some way, a command is applied to the error detector. This device receives data from both the input source and the controlled output device.
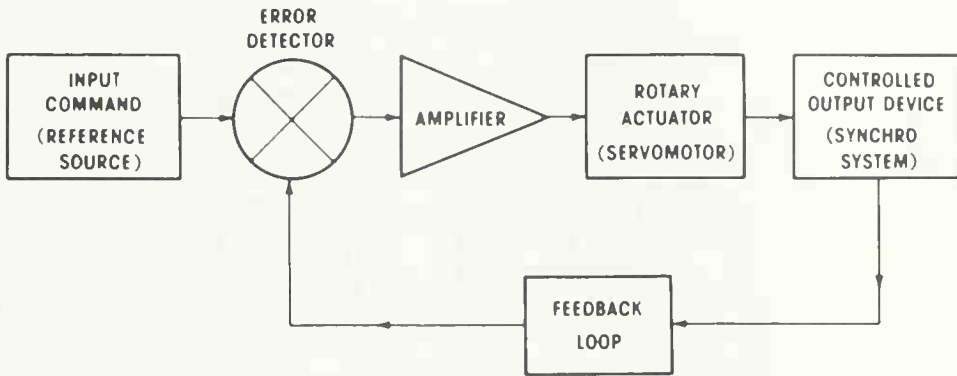
Figure 8–11. Block diagram of a typical servo system.

If a correction is needed with reference to the input command, it is amplified and applied to the actuator. The actuator is normally a servomotor that produces controlled shaft displacements. The controlled output device is usually a synchro system that relays information back to the error detector for position comparison.

Servomotors. A servomotor is a special type of device that is used to achieve a precise degree of rotary motion. Motors of this type must first be able to respond accurately to signals developed by the system's amplifier. Secondly, they must be capable of reversing direction quickly when a specific signal polarity is applied. Also, the amount of torque developed by a servomotor must be quite high.

Two distinct types of servomotors are used today to achieve these operating conditions. A single-phase ac type of motor, called a *synchronous motor*, is commonly used in low-power applications. Excessive amounts of heat developed during starting conditions normally limit this motor to rather low-output-power applications. Direct current *stepping motors* are another type of servomotor.

ac Synchronous Motors. The construction of an ac synchronous motor is quite simple. It contains no brushes, commutators, or slip rings. As shown in Figure 8–12, it is simply made up of a rotor and a stator assembly. There is no direct physical contact between the rotor and stator. A carefully maintained air gap is present between these two parts. This motor has a long operating life and is highly reliable.

The speed of a synchronous motor is directly proportional to the frequency of the applied ac and the number of pairs of stator poles. Since the number of stator poles cannot be altered after the motor has been manufactured, frequency is the most significant speed factor.
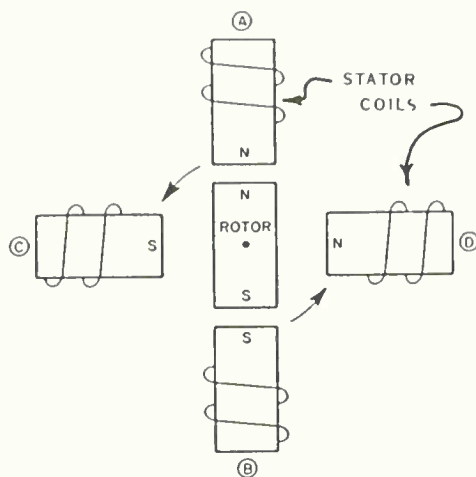
Figure 8–12.   Construction of ac synchronous motor.

Speeds of 28, 72, and 200 rpm are typical, with 72 rpm being a common industrial numerical control standard.

Figure 8–13 shows the stator layout of a two-phase synchronous motor with four poles per phase. Poles N_1-S_3 and N_5-S_7 represent one phase while poles N_2-S_4 and N_6-S_8 represent the second phase. There are places for 48 teeth around the inside of the stator of Figure 8–13. One tooth per pole, however, has been eliminated to provide a space for the windings. Five teeth per pole, or a total of 40 teeth, are formed on the stator. The four coils of each phase are connected in series to achieve the correct polarity.

The rotor of the synchronous motor is a permanent magnet. There are 50 teeth cast into its form. The front section of the rotor has one polarity while the back section has the opposite polarity. The physical difference in the number of stator teeth (40) and rotor teeth (50) means that only two teeth of each part can be properly aligned simultaneously. With one section of the rotor being a north pole and the other section being a south pole, the rotor has the ability to stop very quickly. It can also produce complete direction reversals without hesitation because of this gearlike construction.

The synchronous motor has the capability of starting in one and one-half cycles of the applied ac frequency. In addition to this, it can be stopped in five mechanical degrees of rotation. These two characteristics are primarily attributed to the geared rotor and stator construction. Synchronous motors of this type have one other important characteristic. They draw the same amount of current from the power source
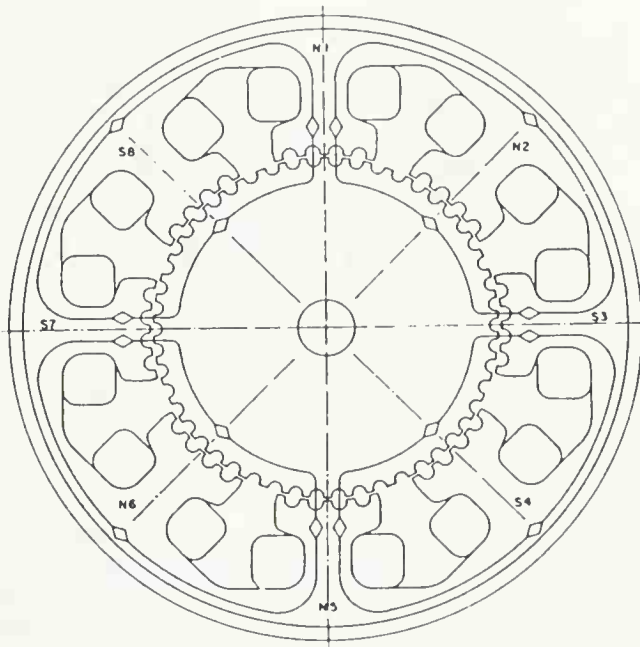
Figure 8–13. Stator layout of two-phase synchronous motor. (*Courtesy of Superior Electric Co.*)

when stalled that they do when operating. This characteristic is very important in automatic machine tool applications where heavy mechanical loads are used.

dc Stepping Motors. Direct current stepping motors are rotary actuators that are used in the control of automated manufacturing systems. Motors of this type are found in nearly all high-power servomechanisms. They are more efficient and develop significantly more torque than the synchronous servomotor. The stepping motor is used primarily to change electrical pulses into rotary motion that can be used to produce mechanical movement.

The shaft of a dc stepping motor rotates a specific number of mechanical degrees with each incoming pulse of electrical energy. The amount of rotary movement or angular displacement produced by each pulse can be repeated precisely with each succeeding pulse from the drive source. The resulting output of this device is used to accurately locate or position automatic process machinery.

The velocity, distance, and direction of a specific piece of equipment can be moved or controlled by a dc stepping motor. The movement error of this device is generally less than 5 percent per step. Motors of

SWITCHING SEQUENCE*

STEP	SWITCH #1	SWITCH #2
1	1	5
2	1	4
3	3	4
4	3	5
1	1	5

* To reverse direction, read chart up from bottom.
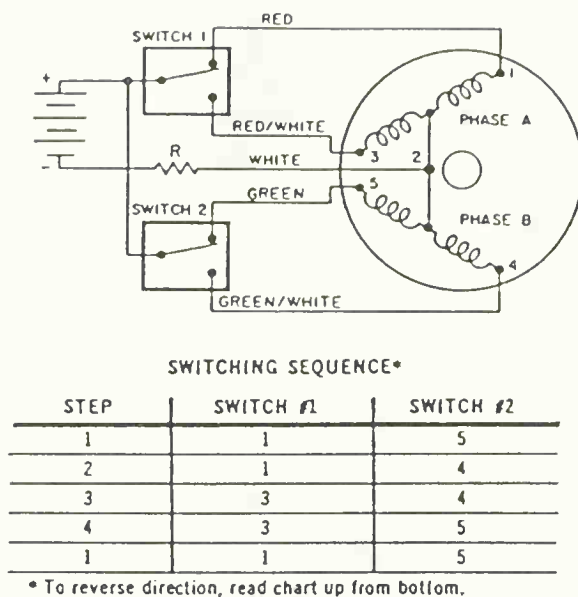
Figure 8–14.   Diagram of dc stepping motor. (*Courtesy of Superior Electric Co.*)

this type are energized by a dc drive amplifier that is controlled by a computer system.

The basic construction of a dc stepping motor is very similar to that of the ac synchronous motor. The stator construction and coil placement are the same as that of the synchronous motor layout shown in Figure 8–13. One manufacturer makes some servomotors that can be operated as either an ac synchronous motor or as a dc stepping motor. The rotor is a permanent magnet on this machine.

Figure 8–14 shows an electrical diagram of a dc stepping motor. The stator coils of this motor are wound by a special type of construction called *bifilar*. Two separate wires are wound into the coil slots at the same time. The two wires are smaller in size, which permits twice as many turns as with a larger-sized wire. Construction of this type simplifies the control circuitry and dc energy source requirements.

Operation of the stepping motor of Figure 8–14 is achieved in a four-step switching sequence. Any of the four combinations of switches 1 or 2 will produce an appropriate rotor position location. After the four switch combinations have been achieved, the switching cycle repeats itself. Each switching combination causes the motor to move one-fourth of a step.

A rotor similar to the one shown in Figure 8–13 has 50 teeth. Using this rotor in the circuit of Figure 8–14 would permit four steps per tooth,

Figure 8–15. dc stepping motor. (*Courtesy of Superior Electric Co.*)

or 200 steps per revolution. The amount of linear displacement, or step angle, of this motor is, therefore, determined by the number of teeth on the rotor and the switching sequence.

A stepping motor that takes 200 steps to produce one revolution will move 360°/200, or 1.8° per step. It is not unusual for stepping motors to use eight switching combinations to achieve one step. In this case each switching combination could be used to produce 0.25° of linear displacement. Motors and switching circuits of this type permit a very precise type of controlled movement. Figure 8–15 shows a dc stepping motor, similar to those used with robotic systems in industry.

Power Supplies for Industrial Robots

The power supply of an industrial robot provides energy to operate the actuators of the system. There are three major types of power supplies: (1) electrical, (2) hydraulic, and (3) pneumatic. Electrical power supplies require less floor space and provide low-noise operation. Hydraulic power supplies may be used to move heavy objects and are faster and more accurate than electrical supplies. Pneumatic power supplies are used for light application and have good speed and accuracy.

Actuators for Robotic Systems

Most robotic systems use either electrical, hydraulic, or pneumatic actuators. Electrically operated robotic systems are usually driven by dc stepping motors. These systems are not as powerful or as fast in operational speed as hydraulic units; however, they have better accuracy and repeatability and require less floor space. Hydraulic robotic systems

have fewer moving parts and are stronger and faster in operation. Pneumatic actuators are ordinarily used for small, limited-sequence pick-and-place operations.

Overload Protection

The end effectors of industrial robots should have some type of protection against overload conditions which may occur. Ordinarily, such protection causes a feedback signal to the computer system to withdraw the manipulator before damage occurs. Methods used to provide "breakaway wrists" or rapid withdrawal of a manipulator include mechanical fuses, detents, and preloaded springs. *Mechanical fuses* are pins or tubes that break or buckle under extreme stress conditions. *Detents* are two or more elements which are held in position by spring-loaded detent mechanisms. They are caused to move from their original positions under excessive stress. *Preloaded springs* may also be used to prevent overload conditions. They are placed in an end effector so that excess stress will cause the spring to release and the end effector will break away from the work area. These devices are desirable to use since they will reset automatically when the overload is removed. Mechanical fuses are less desirable since they must be replaced, but they are not as expensive as other overload protective devices.

REVIEW QUESTIONS

1. In what ways do industries use electrical energy?
2. What are some methods of producing electrical energy?
3. What are the basic parts of an electric motor?
4. What is the relationship of load, speed, cemf, current, and torque in an electric motor?
5. How is the horsepower of a motor determined?
6. What are some types of dc motors?
7. What are some types of single-phase ac motors?
8. How is the speed of an ac induction motor determined?
9. What are some types of three-phase ac motors?
10. What is a synchro system?
11. What is a servo system?
12. What is a dc stepping motor?
13. What types of power supplies are used for industrial robots?
14. What is the purpose of overload protection for industrial robots?

NONINTELLIGENT CONTROLLERS

There are more than 200 robot controllers on the market today which range in price from several hundred to several thousand dollars and in sophistication from a few relays to powerful minicomputers. Regardless of the cost or sophistication of a controller, its basic task is to position the end effector at the right place at the right time. Any controller must be able to "remember" and "recall" the sequence of steps needed to perform the task being supervised. The memory of the controller must be changeable to allow the robot to be reprogrammed for a new or altered task.

In an earlier chapter robots were classified as nonintelligent, intelligent, or highly intelligent. The intelligence of a robot depends largely on the capabilities of its controller and sensors, which can also be classified as nonintelligent, intelligent, or highly intelligent. Differences among levels of intelligence lie in the areas of feedback, decision-making capabilities, and communication with other controllers. The advent of the microprocessor, an inexpensive yet powerful computer, has produced a dramatic increase in the level of intelligence in recent years.

Nonintelligent controllers are open-loop controllers. They do not accept feedback information from the robot about the current position and velocity of the end effector. Such a controller merely cycles the end effector through a sequence of preprogrammed steps without regard to

changes that occur in the system which might affect the actual position of the end effector. They merely play back the program they were taught. The actions of these controllers are based on the assumption that the end effector really is where it should theoretically be. Intelligent and highly intelligent controllers are closed-loop controllers. They accept position and velocity feedback from the robot and generate correction signals which position the end effector correctly despite any changes which have occurred.

Nonintelligent and intelligent controllers have a limited capability to communicate with other controllers used in a manufacturing process. Highly intelligent controllers can accept information from vision, touch, and other external sense controllers about the current position of the end effector. Many assembly tasks are not feasible without such external feedback. Highly intelligent controllers can also exchange status information, program data, and commands with supervisors and coprocessors in a computer-controlled manufacturing system.

Nonintelligent controllers generally supervise hydraulic or pneumatic pick-and-place robots which are operated by actuating valves to control the flow of fluid in the cylinders that make up the robot's arms and joints. When a valve is actuated, the cylinder extends or retracts until it hits a mechanical stop which is positioned along the cylinder by the robot user. Fluid valves may be operated mechanically by pressing and releasing a plunger or operated electrically by supplying power to a solenoid which opens and closes the valve.

Rotating Drum Controllers

In the early 1970s rotating mechanical drums were often used as controllers. Cams are placed on the surface of the drum and the valve plungers pressed and released as the drum rotates or the cams activate relays which in turn control the valves. A cam's size and position on the drum make up the controller's memory and determine when a particular valve will be opened and how long it will remain open. The rotational speed of the drum determines how quickly the task is performed. A rotating drum controller is programmed by the selection and arrangement of the cams on the drum and the setting of mechanical stops on the robot cylinders to control the travel of the arm. Once set up, a rotating drum controller may perform reliably over a long period of time. A drum controller does not have the ability to change the sequence of motions being controlled based on feedback about the current position of the end effector or the progress of the process in which the robot is participating.

Air Logic Controllers

Air logic controllers were also used in the late sixties and early seventies on some robots. Air logic control involves physically positioning the mechanically operated valves at the end of a cylinder's desired travel so that when the cylinder reaches the desired position it actuates the next valve in the process. Air logic must be custom designed for each robot application and a program is not easily changed. Air logic controllers do not accept feedback or have the ability to communicate with other controllers. Since no electrical contacts are involved, air logic controllers were often used in explosive and corrosive environments.

Relay Logic Controllers

Electromechanical relays were also used as controllers in the sixties and seventies. A relay controller consists of a series of relays which activate solenoid-controlled fluid valves; as the relays are activated, the valves are opened and closed to move the arm. Relays in the controller are connected to limit switches mounted on the cylinders near the stops, to other relays in the controller, and to electric or pneumatic timers to control the sequencing and timing of valve actuation. The sequencing and timing of valve actuation is controlled by the circuit made of the interconnections of the relays, limit switches mounted on the cylinders, and electric timers. The robot's task is programmed by first producing a "ladder diagram" of the needed relay to limit the switch to the timer connections and then wiring the control circuit. The order of electrical connections between the components creates the memory in a relay controller. Relay controllers are more difficult to reprogram than drum controllers since each change in the program requires a wiring change between the switch, relay, and timer components. All of these components are susceptible to both mechanical and electrical wear and require routine maintenance. Relay controllers were commonly used as industrial process controllers and their application to robotics was a natural development.

Rotating drum, air logic, and relay controllers are not being used in current controller design. Four factors led to their demise. First, the programs are not easily changed as details of the task being performed change. Second, these controllers cannot communicate with other controllers involved in the process or with supervisory controllers which may need to alter the current task. Third, these controllers are susceptible to mechanical and electrical wear and require routine maintenance. Fourth, and most important, less expensive electronic controllers have appeared which do not suffer from the first three problems.

Development of Computer Controllers

In the mid-1960s integrated circuits (ICs), or chips, were developed. An IC is the fabrication of a complete, multiple transistor circuit on a single silicon wafer. Early ICs held 25 or 30 transistors in a circuit about 8 mm. square. IC research and development efforts were intense in the area of computer logic circuits and the availability of digital ICs allowed the production of small, relatively inexpensive yet powerful minicomputers in the late 1960s. A relatively inexpensive minicomputer in that era cost about $50,000—not inexpensive enough to be competitive with drum, air, or relay controllers for the simple pick-and-place robots available. Digital ICs, the components of the minis, were, however, quickly used in controllers. Like relay controllers digital IC controllers were hard-wired; the controller was programmed by the wiring connections between the many ICs used; and like relay controllers a program change required a change in the wiring between the ICs. Generally, the same ladder diagram used for a relay controller was used for an IC controller. IC controllers were often used as direct replacements for relay controllers. As such they offered the advantages of greater reliability, less maintenance, and sometimes lower cost. They were not, however, programmable computers.

The number of transistors which could be placed on a chip continued to increase throughout the early 1970s. Since a computer's power is roughly proportional to the number of transistors in its ICs, minicomputers became smaller, more powerful, and less expensive in the early 1970s. As a result of the decrease in price, minicomputers began to see limited use as robot controllers. In 1974 Intel introduced the first microprocessor—the 8080—and the world of control would never again be the same. A microprocessor is the heart of a computer on a chip and, although crude by today's standards, the 8080 could be combined with two dozen other inexpensive ICs to form a small inexpensive computer system. In 1975 such a system typically cost less than $1000 and had very little power compared to a minicomputer but had much more power and flexibility than drum, air, and relay controllers. The late 1970s saw exponential growth in the power of microprocessors so that by the early 1980s the system of 1975 could be fabricated on a single chip for less than $10. State-of-the-art microprocessors are more powerful than minicomputers were five years ago at a fraction of their cost. As the cost of the computer itself has decreased, so too has the cost of such essential peripherals as disk drives, terminals, and printers. The importance of the development of IC-based controllers cannot be understated. Advancements in robotics have primarily been advancements in controllers, and today practically all controllers are computer based. Inexpensive computer controllers make hierarchical control, vision, and touch economically feasible.

The computer offers four advantages over other electrical and mechanical controllers. First, a computer's program is stored as an electric or magnetic charge and can be changed without a mechanical adjustment. Changing the program involves changing the contents of a computer's memory—not the physical memory unit itself. Down time for reprogramming is therefore much less than with the other types of controllers discussed. Second, a computer has the ability to make decisions based on feedback information and to change its program as the task is being performed. Use of the computer allows the process to be described mathematically and precisely changed as needed. Third, a computer has the ability to communicate with other controllers and to coordinate its efforts with other machines under the direction of a supervisor. Fourth, ICs are solid-state devices. All decisions about the timing and sequence of robot operations are made by the movement of electrons through silicon. Computers have no moving parts, so routine maintenance is minimal.

Programmable Controllers

One of the earliest applications of microcomputer technology to robot controllers was the programmable controller shown in Figure 9–1. A programmable controller (PC) is a computer-based emulator of relay logic. Programmable controllers were developed for use as replacements for relay logic process controllers. A ladder type diagram is developed that describes the sequence and timing of the robot. The user then programs the PC through a detachable keyboard by specifying the sequence and duration of switch, relay, or solenoid valve closings to move the robot's arms. Symbols for switches, relays, and timers appear on the keyboard along with the few commands that exist. Programming a PC is relatively simple and straightforward; the programmer does not need to know a computer language. A user with relay logic experience can learn to program a PC in just a few hours. The program is stored in solid-state memory and replayed each time the robot is operated. The program may be executed a single step at a time and can be easily edited from the keyboard with any changes being stored in memory. A programmable controller also includes a standard interface that boosts its low power output to drive solenoids or relays and to protect it from the electrically noisy manufacturing environment. Most PCs are modular in design, and each has a logic unit and a backplane connector that can accept various combinations of input and output modules. The PC is configured to meet the I/O requirements of a particular robot. It is usually housed in a steel cabinet that may range in size from a breadbox to a filing cabinet. PCs are usually sold as complete systems; the user must supply only the connections to the robot and the program.
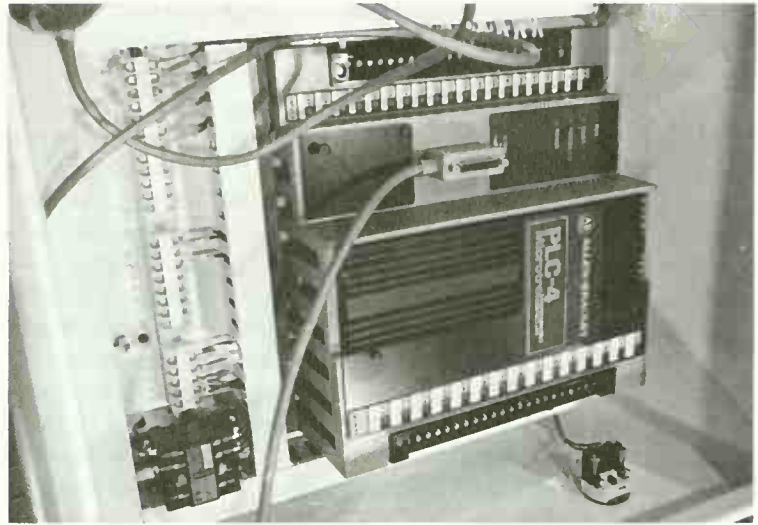
Figure 9-1. Programmable controller. (Photo taken at Robot 7 show.)

The PC is a rather low-level microcomputer application. While some PCs include the capability to manipulate input information mathematically or communicate with other controllers, these abilities are generally unused in a pick-and-place robot. The computer is hidden from the user by a built-in program which makes the PC appear to be a relay logic controller. Although this program greatly eases the programming and editing tasks for users not familiar with traditional computer controllers, it limits the PC's ability to make decisions and communicate with other controllers. This trade-off is usually favorable since the pick-and-place robot being controlled does not have the ability to alter its movements on command from the controller; it must be physically reprogrammed by moving the mechanical stops that limit the arm's travel. Ease of creating and editing programs, high reliability, and relatively low cost have made PCs popular with users of nonintelligent robots. Several manufacturers market a variety of PCs.

Single-Board Controllers

Some general-purpose, single-board, control microcomputers are used as nonintelligent controllers. These controllers must usually be programmed in the microprocessor's machine language, a difficult task at best. A few vendors are selling development packages for these controllers that can be run on popular desktop microcomputers. A devel-

opment system is a special program and circuit board that allows the user to specify the control task in terms of a relay logic ladder diagram. The development system then generates the machine language program needed by the single-board controller and stores it in a memory chip which can then be plugged into the controller. The advantage of the single-board controller is its very low price, typically under $500. The disadvantage of a single-board controller is that the user must have the expertise to specify and assemble a control system from board level components including the controller board and any interface boards that are needed to drive the relays or solenoids as well as the power supply, backplane connector, and cabinet.

REVIEW QUESTIONS

1. List the major differences between mechanical and electronic controllers.
2. Explain why nonintelligent controllers are appropriate for use with pick-and-place robots.
3. Explain the operation and programming of a rotating drum controller.
4. Explain the operation and programming of a relay logic controller.
5. Discuss the impact of integrated circuits on the sophistication level of robot controllers.
6. List two advantages of a programmable controller over a relay logic controller.
7. Explain the operation and programming of a programmable controller.
8. Discuss the advantages and disadvantages of a single-board controller.

Chapter 10

COMPUTERS IN CONTROL

Just as the development of the IC brought about the end of drum and relay controllers, the development of the microprocessor will lead to the end of nonintelligent controllers. Today the cost of a relatively sophisticated single-board computer is lower than the cost of a digital IC controller and lower than the cost of most programmable controllers. Even the least intelligent pick-and-place robots will have computer controllers, simply because they are less expensive than other types of controllers. This chapter will examine the components of the computer as it is used in robot controllers.

Computer Diagram

Figure 10–1 shows the block diagram of a typical computer system. The center block, the microprocessor unit (MPU), is what usually comes to mind when a computer is mentioned. The MPU consists of one or perhaps a few ICs and is capable of performing a well-defined set of rather simple tasks on data. This set of tasks is called the processor's instruction set. Instructions may be given to the MPU in many forms, or languages, but it is important to understand that the MPU can do only one thing: execute instructions. The computer user must, then, produce or buy a
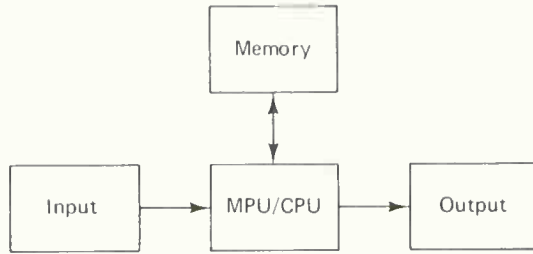
Figure 10–1.   Computer system.

program that lists those instructions needed to perform the desired system task in the order of their performance. Although the instructions tend to be relatively simple operations, the MPU can execute a single instruction in a few millionths of a second. To take advantage of this speed, a program is stored in IC memory chips. When a program is executed, the MPU fetches each instruction in turn from the memory. Memory ICs can respond to the MPU's rapid demands for instructions without slowing its execution rate. The system is programmed and receives data through an input section. The MPU transmits commands and data to the outside world through the output section. Input and output (I/O) units include ICs and other electrical control components. All of the blocks in Figure 10–1 and the components in the blocks are collectively called *hardware*. The program that includes the sequence of instructions needed to control the robot is called *software*. A computer's hardware is software driven; that is, unless there is a program or software routine in memory for each task required of the computer, the hardware will not function.

The general-purpose computer is shown in Figure 10–2 as a robot controller. The input devices that feed a computer controller may include position sensors located on the arm, other controllers involved in the operation, and the programming terminal. Output devices may include arm position and velocity controllers, other process controllers involved in the process, and the programming terminal. Memory includes devices for storage of both the control program and data about the current position and velocity of the arm and any other information pertinent to control of the arm.

The MPU

Both minicomputers and microcomputers are commonly used as controllers today. It used to be easy to distinguish between minis and micros. Minis were organized around 16-bit binary words while micros
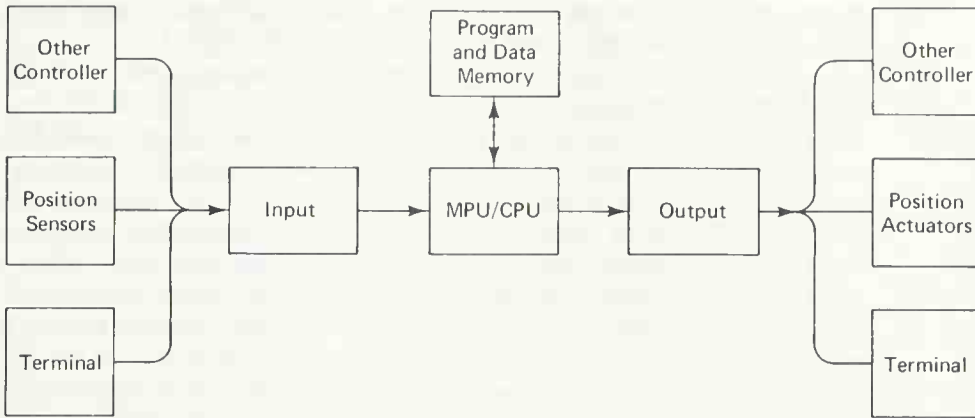
Figure 10–2. Computer controller.

were organized around 8-bit binary words. Minis were faster, had more powerful instruction sets, and cost about ten times more than micros. Today's micros have grown to use 16-bit words and more powerful instruction sets, but minis now use 32-bit words and even more powerful instruction sets. Minis are still more expensive than micros. Micros have generally replaced minis in intelligent controllers and are being seen more frequently in very intelligent controllers. Minis will still be found in very intelligent controllers and in older-design intelligent controllers. The task performed by either type of MPU is the same, to fetch instructions from memory and to execute them. Both types of MPUs perform this task in the same manner; differences are generally in the speed at which an instruction is executed, the sophistication of the instructions used, the amount of memory that can be directly accessed, and the cost.

The most widely used minicomputer is Digital Equipment Corporation's PDP 11. First introduced in the early 1970s, the PDP 11 was the choice of controller designers throughout the decade. The PDP 11 is a powerful, general-purpose 16-bit computer that has been well supported by DEC and many other manufacturers with a wide variety of hardware and software. The PDP 11 is available in configurations that range from a single-board LSI 11 MPU to complete assembled systems including memory and I/O. These systems range in capability from the low end of the minicomputer spectrum, which can easily be replaced by a microcomputer, to the high end, which rival small mainframes in power. The price of a PDP 11 system has continually fallen because DEC has implemented it in new generations of IC fabrication technology. The result today is a physically smaller machine that has fewer ICs. The PDP 11 and newer VAX are presently being used in some intelligent and

many very intelligent controller designs. Other minicomputers are used as controllers, but none rivals the popularity of the PDP 11.

Although there is not a single dominant microcomputer currently being used in controllers, Motorola's 68000 and Intel's 8086 16-bit and Zilog's Z80 8-bit microprocessors have been popular with designers because of their great power and low price. The 16-bit systems are widely used in both intelligent and very intelligent controllers; the 8-bit systems are more common in intelligent controllers. While most minicomputers used today are off-the-shelf general-purpose computers, most microcomputers are custom-designed units that are more likely to be a collection of off-the-shelf circuit boards which have been assembled into a system. Often, a system designer will use boards that are plug compatible with a popular connector or "bus" standard. Such systems are then advertised as being compatible with that bus. The Multibus, the Versabus, the VME, and the S100 are popular microcomputer connector buses. Systems can be configured using the 68000 or 8086 microprocessors, which rival the power of small- to medium-sized minicomputers at lower prices. Although either of these chips can be purchased for less than $100, it must be surrounded and supported by several other chips. Therefore, final system cost may range from several hundred to several thousand dollars depending on the power of the system. Because of their recent introduction there are not as many system development tools available for the 16-bit machines as for a typical minicomputer, but the microprocessor manufacturers and third-party software houses are quickly filling the void. Microcomputers are now widely used in intelligent controllers and are appearing in very intelligent controllers. This trend will no doubt accelerate as the 32-bit word microprocessors are brought to market. It appears that the micro will replace the mini in all but the most intelligent controllers and that minis will become supervisors of micro-based controllers in automated manufacturing systems.

Memory

The program used by the MPU to direct the robot's movements and the positional data used by the program are stored in the computer's memory. A computer's memory can be classified as either on or off line. On-line memory is that shown in the block diagram of Figure 10–2. On-line memory is directly connected to the processor which has immediate access to its contents. Off-line memory is not connected directly to the MPU; instead it is connected to the system's on-line memory. Information stored in off-line memory must be transferred into on-line memory before the processor can access it.

On-line memory is generally IC memory. IC memory can be classified as random-access memory (RAM) or read-only memory (ROM).

RAM stores programs or data as electronic charges within the silicon semiconductor material which makes up the IC. The contents of RAM can be readily changed by the MPU, so it is used to store the current position of the arm or a different sequence of motions for the arm which have been entered by a supervisory computer or the operator. The storage capacity of RAM has increased dramatically in the last ten years so that a circuit which contains eight IC RAMs can store 256,000, or 256K, characters. Other popular RAMs have capacities of 64K, 16K, 2K, and 1K. The particular RAM chosen depends on the overall intelligence of the controller in which it is used; generally the smarter the controller, the more memory it needs. The primary disadvantage of RAM is its need for constant power. Without power RAM loses its contents; it forgets the information it was storing. Some controller manufacturers overcome this problem by maintaining power to the RAM circuits at all times. Others include rechargeable batteries which automatically power the RAM when main power is interrupted. The danger of losing power to RAM is the loss of program or positional data which must be reloaded. Reloading a program or database into RAM means down time for the system. If the lost program was an edited version of the existing copy, the down time needed to tweek the program back to the previous performance levels may extend the down time. The need to quickly make copies of programs as they are edited, to reload programs when they are lost, or to load a new program or database is filled by off-line storage devices.

Two types of devices represent solutions to the power problems of RAM. ROM is IC memory that doesn't forget when power is removed. A ROM chip can be removed from a circuit, placed on a shelf for years, then placed back into a circuit without losing its contents. ROM chips have storage capacities equal to those of RAM. The disadvantage of ROM is that its contents are not easily changed. Information is programmed into the circuitry of a ROM chip when it is manufactured and it can never be changed. A change in program means discarding the old ROM and replacing it with a new one which contains the desired changes. The special tooling required to program ROM is quite expensive and forces ROMs to be used only in those applications when the cost can be spread over thousands of devices. A special type of ROM called an EPROM can be programmed by the user and is much less expensive in small quantities than ROM. An EPROM can also be erased and reprogrammed but not while in the controller circuit. It must be removed from the circuit, erased with ultraviolet light, reprogrammed in a special EPROM programmer, and then finally put back into the controller circuit. EPROM programmers cost about $2000 and can program an EPROM in a few minutes. Electrically erasable ROMs (EEPROMs or EAROMs) have been introduced and are being used in some control-

lers. These devices do not require ultraviolet light for erasure so may be reprogrammed in-circuit. EEPROMs are more expensive than EPROMs but less expensive than ROMs. ROMs and EPROMs are used to store information that doesn't change. System software that supports the execution of the user's robot control program is stored in ROM. A robot program that will be used for a long period of time without change may be stored in EPROM. These programs are usually developed remotely where an EPROM is burned or programmed. The new program in EPROM is then installed in the controller by a technician who replaces the old EPROM which may be reused with the next program change. Few controllers include EPROM programmers.

A recent alternative to RAM and ROM is magnetic bubble memory. Bubble memory consists of a thin layer of magnetic material in which small magnetic domains or bubbles may be induced. Data is stored in patterns of bubbles created in long chains within the material. The MPU can readily change the data stored by the bubbles. Since the magnetic bubbles remain when power is removed, constant power is not needed to retain the contents of memory. Bubble memory offers the advantages of both RAM, which is changeable, and of ROM, which does not need constant power. Bubble memory is usually packaged in IC-like packages and can typically store 256K characters. There are two disadvantages to using bubble memory. Bubble memory requires a few special data manager chips to support its communications with the MPU, which may slow the MPU's execution rate. The other disadvantage of bubble memory is its high cost relative to semiconductor memory. Presently some manufacturers are using bubble memory in controllers, and as its price decreases it will be used more frequently.

Off-line memory is either magnetic tape or magnetic disks. The magnetic tape systems generally use standard cassettes in slightly modified cassette decks. These systems convert the binary data used by the MPU into audio tones which are stored on the tape. Cassette tape systems transfer data to or from on-line memory very slowly compared to the rate of transfer between the MPU and on-line memory. The tape decks used do not have special transport controls so that access to the programs and data stored on a tape is sequential. That is, the deck must read past all of the data or programs stored on the tape in front of the desired data before it can read the data desired. Sequential access is very slow. Cassette systems are only used to hold back-up or archival copies of the programs and databases used by a controller. The programs are transferred into and used from RAM and are only loaded from tape when they are lost due to a power outage or when the robot is given a new task. The cassette deck is an option in many systems and is plugged into the controller only when needed. The primary advantage of using tape for off-line storage is its low cost. A cassette deck may cost as little

as $100. In systems that do not require frequent loading of new programs, the slow data transfer rate is offset by the cost.

Magnetic disks, often called floppy disks, store data as magnetic patterns on a thin flexible disk which has been coated with magnetic particles. Although disks are available in sizes of 8, $5\frac{1}{4}$, and $3\frac{1}{4}$ in. in diameter, currently the $5\frac{1}{4}$-in. disks are the most widely used. A disk is encased in a square rigid envelope to protect its magnetic coating from dust and dirt. Information is read from and written to the disk by a disk drive. A drive includes a read-write head that contacts the magnetic surface of the disk through an oval slot in the envelope, a drive motor that spins the disk, and an electronic controller that controls the drive motor and the head-positioning stepper motor. A special program called the disk operating system (DOS) is executed by the processor to supervise the writing and reading of information to and from the disk. The DOS, which is generally invisible to the user, maintains a directory on each disk which includes the name and location of each file. Some systems store the DOS in ROM while others store it on a disk and load, or boot, it into RAM when the system is powered up. The disk occupies the same position in a system as a cassette—data stored on a disk cannot be directly used by the MPU but must first be loaded into RAM. The storage capacity of a disk depends on the drive mechanics and electronic controller circuitry used and may range from 85K characters for a single-density $5\frac{1}{4}$-in. drive to 180K characters for a double-density $5\frac{1}{4}$-in. drive. Single-sided drives store information on only one side of a disk while double-sided drives have two read-write heads and store information on both sides of a disk. A double-sided, double-density drive may have a capacity of 360K characters.

The disk offers two great advantages over the cassette as an off-line storage device. First, the programs and databases stored on a disk can be accessed at random. The controller electronics, under direction of the DOS, can position the read-write head over any file on the disk within less than 20 msec. Search time is, therefore, minute compared with that of a cassette drive, which must read past all preceding information on a cassette before it can read from or write to the desired file. The rate of data transfer to and from RAM is much greater for a disk than for a cassette. A program or database can be loaded into RAM 10 to 100 times faster from disk than from cassette. Because they provide nearly instant access to programs and data, disks contribute to the intelligence of a controller. Disk-based intelligent controllers can direct the robot to perform complex tasks which require databases too large to reside in RAM. Data is transferred from the disk into RAM in sections as it is needed with the disk running sporadically throughout the program.

Winchester and the microfloppy disk drives are beginning to see

use in very intelligent controllers that may require access to millions of data points. The Winchester disk packs the data much closer together on a rigid disk, enabling a $5\frac{1}{4}$-in. disk to hold more than 20 million characters. Winchester drives are available with removable disks which cost about $60. These drives are highly sensitive to dust particles and although they include air filtration systems, air quality problems may exist when used in controllers located on the shop floor. Winchester drives are more expensive than floppy drives, but the price differential is narrowing rapidly. The $3\frac{1}{4}$-in. drive, commonly referred to as a microfloppy, uses a diskette housed in a hard plastic case which can be carried in a shirt or jacket pocket. A microfloppy has a 500K storage capacity and two microfloppy drives can be placed in the space of a single $5\frac{1}{4}$-in. drive. Widespread use of the microfloppy has been hampered by the lack of industry standards, and several noncompatible versions of the microfloppy are being marketed.

Since the MPU in the controller is directed by the program stored in memory, the amount of memory available in a controller is a measure of its intelligence. The trend to more memory in less space at lower cost has contributed greatly to the increased intelligence of controllers. It appears that this trend will continue and memory improvements will keep pace with improvements in the MPUs.

I/O Interface

The MPU and memory components of a controller do not work in an information vacuum. The program and database must be fed to the controller before it can perform the desired task. Information about the current position and speed of the end effector and other external conditions is supplied to the controller by sensors on the arm and end effector. Information that will direct the movement of the arm and the end effector is constantly generated by the controller for use by the electromechanical components of the arm. Information gathered for use by the controller is referred to as input data. Information generated by the controller for use by the electromechanical system to position the arm is referred to as output data. Collectively, input and output data are referred to as I/O.

Input data enters the controller system through an input port, and output data leaves the controller system through an output port. An input or an output port is an IC that connects the MPU to sensors and electromechanical movers on the arm. The MPU views an I/O port in much the same way it views a memory device; an input operation is much like a memory read and an output operation is much like a memory write. Each MPU family includes several MPU-compatible I/O parts.

The connection of external devices to the controller is not as straightforward as it may seem. The MPU, memory, and I/O ports in the controller require a regulated +5-V dc power supply and have little tolerance for electrical noise or voltages greater than +5 V. The solenoids, valves, steppers, and servos commonly found in the robot arm may require from +12 V dc to 120 V ac. Connecting a powered 120-V ac valve directly to a +5-V dc output port on the controller would result in the immediate and absolute destruction of the output port and most of the rest of the controller. An interface circuit must be placed between the delicate low-voltage, low-current controller and the high-voltage, high-current arm components to protect the controller from the outside world. Interface circuits are generally used with both input and output ports.

An output interface performs two basic tasks: It allows the low-level signals generated by the controller to control the high-power signals needed by the arm movers and it electrically isolates the delicate controller from the high-power world of the arm movers. Traditionally, electromechanical relays and transistors have been used to interface circuits, but today solid-state relays are more commonly used. A solid-state relay includes a light-emitting diode and an optotransistor to provide the required electrical isolation and either an SCR or a TRIAC to perform the power level conversion. The SCR and TRIAC are high-power solid-state switches which are controlled by low-level signals. A solid-state relay connects the low-level output of the controller to the SCR through the LED-optotransistor link. These interfaces offer the no moving parts and/or electrical arcing advantages usually found in solid-state devices. They may be packaged in a *de facto* standard case with easy-access connection terminals. A typical output interface is shown in Figure 10–3.
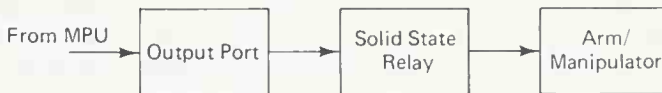
Figure 10–3.   Output interface.

An input interface performs the same functions as an output interface. Input devices provide information about the position and velocity of the arm and end effector. Positional information can be produced by simple on-off mechanical, magnetic, or optical limit switches, which can easily provide both the isolation and controller-compatible voltage levels required. Resolvers are available in controller-compatible and -incompatible versions. Tactile and temperature sense inputs are

Figure 10–4.   Input interface.

generally developed by transducers which produce an analog signal that varies with the energy it is measuring. The analog signal is not compatible with the controller, which uses data in digital, or binary, form. The analog output of a transducer is fed to an op-amp which boosts its analog level. The signal is then passed to an analog-to-digital (A/D) converter chip. The output of the A/D converter is controller compatible and the digital output of the A/D converter is either connected to an input port or serves as an input port. A typical analog input channel is shown in Figure 10–4.

The input of program and database information is generally simpler than control I/O with the arm. RS-232 is a well-established hardware communications standard for the transfer of data between computers, programming terminals, and peripherals. Most currently available vision systems communicate with the controller via an RS-232 link. RS-232 specifies digital bit-by-bit serial communications using voltage levels between ±5 and ±25 V on a standard mechanical connector. Such a standard lends itself to telephone line compatibility, allowing the controller program to be developed on a remote computer system and then transferred into the controller via a phone line. RS-232 is only a hardware standard and does not include the format of data that are transferred. This means that two RS-232-compatible devices may not be able to communicate because they use different data codes or format. Within a single company's product line, however, RS-232 compatibility generally implies communications compatibility.

Both power control and communications interface circuits are commonly assembled into board level system components that simply plug into the controller. Additional I/O interface channels can be added to the controller by plugging in more interface boards.

Environmental Considerations

Computer-based controllers are physically smaller, lighter, more reliable, and more flexible than their electromechanical counterparts. They are, however, more sensitive to their physical surroundings. Robots are often used to perform tasks in surroundings that present a health hazard to human workers. These surroundings may also be hazardous to a controller's health. Extremely high temperatures shorten the life of ICs.

Heat-holding blankets of dust can cover ICs and shorten their life expectancy. Small amounts of dust can scratch and ruin both a magnetic disk and the delicate read-write head within the disk drive. Corrosive fumes or gases can corrode and destroy electric connections between components within a controller. Moderate levels of nuclear radiation can alter the contents of memory and MPU ICs. Power surges that are common in most manufacturing settings can instantly destroy all controller components. These conditions do not prevent the placement of a controller on the shop floor but do dictate their consideration when installing the controller. Placement of the controller enclosure, internal ventilation fans, air filters, dust-free enclosures, power line filters, and other devices can be used to alleviate environmental problems when proper planning occurs before installation.

Controller Maintenance

Because the MPU, memory, and I/O components used in computer-based controllers are commonly found in many other computer applications, routine computer maintenance and repair procedures can be used. The electronic technician who maintains NC (numerical control) and CNC (computer numerical control) machines and computer monitoring or control equipment possesses the skills needed to maintain a computer controller. To aid the technician, some controller manufacturers include diagnostic routines within the operating system software. These routines sequentially test the system and help locate and identify faults.

Controller Standards

Controller standards do not exist within the robot industry. Some controller vendors custom build or buy custom-built controller hardware which uses proprietary signal and connector definitions. Other controller vendors assemble their controllers with off-the-shelf board-level components purchased generally from one of the microprocessor chip manufacturers. Although these controllers are compatible with the microcomputer bus used by the board manufacturer, there are at least half a dozen popular and mutually incompatible microcomputer buses. Compounding the problem is the wide variety of electrical control signals and connectors required by different robots which have the same capabilities.

The total lack of controller and robot control standards within the industry has resulted in the marriage of a company's robot to its own controller. The vast majority of robots are purchased in a robot-controller

package and many intelligent robots include the controller as an integral part of the robot system. The chaining of a robot to a specific controller is both good and bad. Many first-time users want to invest as little money as possible in their first robot, which often serves as a test of the applicability of the robot in their work situation. The complete turnkey system is often the least expensive way to implement a first robot. When a company develops the expertise to specify the components of a robot system, the marriage of robot to controller may hinder the implementation of the most efficient or least expensive system. Controller standards will appear as the industry matures. With controller standards will come the divorce of the robot-controller package and the availability of a wide range of off-the-shelf standard controllers.

Perhaps the greatest advance in robotics has been the transition from electromechanical to computer controller. Programmability, adaptability, and the development of touch and sight are all possible with the computer. Computers have gotten smarter, smaller, and cheaper and will continue to do so.

REVIEW QUESTIONS

1. Sketch the block diagram of a computer used as a robot controller.
2. Explain the role of hardware and software in a controller.
3. Name the minicomputer most often used as a robot controller.
4. What type of memory is used to store operating system software? Why?
5. What type of memory is used to store position and velocity information in the robot? Why?
6. What is the function of an I/O interface?
7. What is RS-232?
8. Discuss the lack of controller standards and its effects on the robot industry.

INTELLIGENT CONTROLLERS

An intelligent controller has the same function as a nonintelligent controller: It directs the motion of the arm and manipulator in time and space by following a sequence of commands stored in its memory. The intelligent controller is smarter than its nonintelligent cousin because it is a closed-loop controller. It has the ability to accept feedback information gathered by sensors about the actual position of the arm and manipulator. The intelligent controller uses the feedback information to generate correction signals which will compensate for errors in the mechanics of the robot and place the manipulator where it is needed. Correction signals based on feedback are automatically generated by system software and are generally invisible to the user, who does not have to develop signal correction routines. Although the intelligent controller is computer based, sophisticated operating system software allows the controller to be programmed by operators who have not previously used a computer. The sophistication of control provided by intelligent controllers ranges from slightly better than a relay controller to nearly as good as could be provided by a general-purpose computer.

Programming Intelligent Controllers

The intelligent controller typically uses an 8- or 16-bit microprocessor, although most older units used minicomputers. The amount of RAM varies from less than 4K to more than 128K depending on the capabil-

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ities. The extensive operating system software that supports programming is stored in ROM and, in some controllers, on cassette and disk. Some intelligent controllers are disk based but most use a cassette deck for long-term program storage. All controllers have needed I/O to input feedback and output control signals to the robot. Most also have the ability to input information from and send control signals to associated equipment.

The intelligent controller offers many of the advantages of a computer without requiring computer programming skills. An intelligent controller is programmed by placing it in the program mode and then moving the manipulator through the steps to be repeated using either a teach handle or a teach pendant. Operating system software automatically samples each axis and records in memory positional information that will be recalled during execution of the program. The user may be able to choose between continuous sampling of the axes for continous-path operation or specified point sampling of the axes for point-to-point operation. The programmer does not need to know about computers or have previous experience with traditional programming languages. A craftsman can easily teach the robot highly skilled tasks. The ease of programming has made the intelligent controller today's most widely used control system.

The simplicity of programming a controller by manually directing it through the desired motions is produced by the execution of programming routines that are part of the operating system stored in ROM within the controller. The user does not program the computer in the traditional sense of choosing from a broad set of executable instructions; he/she only provides data which is used by the existing programming routines. The sophistication of these programming routines determines the ease and flexibility of programming the controller. There are no standards for these routines and they vary greatly in name, form, and level of sophistication.

Intelligent controllers have three major modes of operation: manual, program, and automatic. The names of these modes are not standardized and they are referred to by different names by the various controller manufacturers. This also applies to the specific operations within each mode and even to the number of modes offered on a controller. Some controllers have half a dozen modes which encompass the activities included in the three modes discussed here. The manual mode allows the operator to directly move the arm and manipulator via a pendant or console. The operator has complete control over the arm without respect to an existing program. A new program is not created nor is an existing program altered while in the manual mode. The program mode allows the entry of new programs and the editing of existing programs. In the program entry mode the controller automatically collects data for a program by regularly sampling and storing in RAM the

movements of the arm or specified points along the desired path of movement. In the program edit mode the user can edit a program just created in the program entry mode or a program which has been loaded from tape or disk into RAM. Editing involves changing existing movements, deleting existing movements, or adding new movements. The controller can be directed to execute the program one movement at a time, a technique called single stepping. The user can edit any or all steps as they are executed. Some controllers allow the insertion of breakpoints in the edit mode. A breakpoint is a system instruction that is inserted between two program steps. When the controller encounters a breakpoint instruction, it stops executing the user's program and returns to the program edit mode. Breakpoints can be useful in editing tasks that require intricate movements in relation to the workpiece or work place. The edit mode is used when changes in the parameters of the task require changes in the program. A program may also be edited to tweek it up for higher efficiency. After a program has been entered or edited, the user is given the option of saving the new program on tape or disk. Prudent programming practice dictates that a copy of the program created or edited be saved before it is run in the automatic mode. Saving a program when it is created takes much less time than re-entering it if the system crashes during automatic execution. When a program has been edited to an acceptable level of performance, the previous versions may then be erased. Many controllers allow programs to be named and several named programs to be coresident in memory. A particular program can then be executed by calling its name. In the automatic mode the controller executes an existing program at normal speed with the option to automatically repeat it. Part of the operating system software that is executed during the automatic mode accepts positional information from each joint on the manipulator. This feedback information is compared to the theoretical positional information and correction factors are calculated. These factors are included by the controller when it generates the signals sent to the actuators on the arm. The arm's actual position is held as close as possible to the desired position by the inclusion of the feedback information. This closed-loop control is automatic and totally invisible to the user. Nothing is done during programming to ensure inclusion of the closed-loop correction routines. They are an integral part of the system software which is executed when a program is executed in the automatic mode.

Walk-Through Controllers

The walk-through controller is programmed by attaching a teach handle to the arm, near the manipulator, and physically moving the robot arm through the desired motions. The arm is counterbalanced during pro-

Figure 11–1.   Walk-through controller. (Photo taken at Robot 7 show.)

gramming, which allows the programmer to move the arm with very little effort. The teach handle has one or more buttons which the programmer uses to actuate the manipulator, to start and stop a paint spray or welding tip, and to enter points during PTP programming. In the programming mode a walk-through controller automatically samples the axes and stores robot, or cartesian, coordinates of the desired points in RAM. A walk-through system is shown in Figure 11–1. Walk-through controllers may allow either CP or PTP sampling depending on the nature of the task performed. Some controllers allow CP and PTP sampling to be mixed in the same program to maximize efficiency and precision. When the programming has been completed, the teach handle is removed for automatic execution of the program created.

CP sampling is more desirable for such tasks as spray painting, in which the path taken is critical to performance of the task. A walk-through CP controller can be easily programmed by a skilled painter who has the needed painting skills but lacks computer experience. An intelligent controller usually allows the user to select the sampling rate during CP operation. The rate selected depends on the resolution of movements demanded by the task specifications and the amount of memory available. The greater the sampling rate, the more RAM required to perform a task. Most intelligent controllers come equipped with less than the maximum possible amount of RAM but provide for the addition of RAM as an option. The maximum amount of RAM in an intelligent controller may range from 16K to 256K. Operating system software in some disk-based intelligent controllers supports high sampling rates for long tasks by dividing the program data into blocks or files that will fit

into the system's RAM. During execution, the blocks are read from the disk into RAM as they are needed. Controllers without a disk are limited during CP operation by the size of the system's RAM.

Lead-Through Controllers

The lead-through controller is more common than the walk-through controller. Programming a lead-through unit involves use of a teach pendant which is attached to the controller. A teach pendant or teach box is shown in Figure 11–2. The pendant consists of a keypad and indicators housed in a case with a cable that connects it to the controller. The programmer guides the arm and end effector through the desired motions by pressing keys on the pendant. A pendant keypad includes keys that allow the user to control each joint on the arm and the end effector individually. The user can specify which joints on the arm are to be moved and the direction of movement for each. The velocity of movement is also user selectable. Start and stop keys allow the user to move the arm after the axes involved have been identified. Programming is usually performed at a relatively low speed to allow the programmer maximum reaction time in controlling the movement of the arm. To

Figure 11–2.   Teach pendant. (*Courtesy of Yaskawa Corp.*)

begin a program, the user moves the arm to a predefined home or reference position or the programmer places the arm at a desired position and defines it as the home position. The arm is then moved through the desired path and programmed using the point-to-point technique. At each position or point in space the user wants the arm to pass through, the user presses a "point enter" key on the pendant and the axes' positional information for that point is automatically collected by the controller. Operating system software converts the information into robot, or cartesian, coordinates which describe that position in space. The coordinates are then stored in memory. Programming is easy and although a first-time programmer tends to omit some needed points, the technique is quickly mastered. The program consists, then, of a series of points for which the controller has collected positional data. During automatic execution the controller moves the arm sequentially from point to point in a straight line. Some controllers allow the programmer to specify arcs as the paths between points. The teach pendant includes keys that allow a program to be single-step executed for editing. Points can be inserted, deleted, or changed. The programmer may be able to specify setpoints for more efficient editing. The number of points that may be included in a program varies with the amount of RAM in the controller. A PTP program requires far less memory than a CP program for the same task since each point along the path of movement is not stored in memory during PTP programming. PTP programming is especially suitable for palletizing and other materials handling tasks.

A few controllers are equipped with pendants which include a joystick to control movement of the arm. These controllers can be programmed using either PTP or CP sampling. The joystick gives the programmer walk-through-like control while being able to view the entire arm and surrounding equipment.

Enhanced Capabilities

Controllers at the upper end of the intelligence range include additional programming capabilities. These allow the controller to make decisions based on external events, to control external events, and to allow more efficient programming of repetitive tasks. Most of these controllers include a pause instruction which causes the program to be halted for a specified period of time. After the specified time has elapsed, the program is continued.

Decision making is performed via instructions that are included in the program between entered position points. These instructions may be entered through the pendant on some controllers while they must be entered through the controller console on others. These instructions generally examine one or more external inputs, and based on their con-

ditions, continue execution, alter the sequence of execution, or halt execution. The inputs are numbered and are referred to by their assigned number in the decision-making instruction. The information available at these inputs is typically provided by limit switches attached to equipment which surrounds the robot. A stationary spray-painting robot positioned along a moving line would be programmed to wait until the workpiece has reached a specified location before it begins the spraying operation. This decision can be specified by including a decision-making instruction at the beginning of the program. The instruction would examine an input which is connected to a limit switch located along the moving line and is tripped by the moving workpiece. The user can generally specify one of three kinds of actions to be taken after a condition is examined. The instruction can simply halt execution of the program and wait until the specified condition is in the desired state before resuming execution. The instruction can halt execution of the program and wait a specified period of time, after which execution is resumed. The instruction can continue normal execution of the program or jump ahead in the program, skipping the points jumped. The jumping or branching capability gives the controller the flexibility to automatically adjust for use of different workpieces with a single program.

Another powerful group of instructions enables the system to control external events. These output instructions send a signal to a specified output device. External output devices, like external input devices, are referred to by number. An output may be interfaced to surrounding equipment through solid-state relays or to other process controllers. An output instruction sends the specified output device a signal which will place it in a specified on or off state, toggle it to the opposite state, or pulse it on or off. The output instructions are included in a program between entered position points. A robot loading and unloading a press might be programmed to output a signal to start the press after a blank has been loaded. The controller would then monitor an input line connected to and used by the press to indicate completion of the operation and availability of the part for removal. The combination of input, output, and decision-making instructions gives the controller great flexibility in working with surrounding equipment.

The repeat and step and repeat instructions are especially useful for palletizing tasks. The repeat instruction allows the programmer to specify that a movement, a group of points, or an instruction be repeated a specified number of times without duplicating the points or instructions in the program. The repeat instruction sets up a controlled software loop. Some controllers identify the points or instructions to be repeated as a named or numbered subroutine. The user, then, specifies the number of the subroutine to be repeated and the number of repetitions to be performed. The automatic mode software then re-executes those

Figure 11–3. Controller console with pendant. (Photo taken at Robot 7 show.)

points or instructions identified as the subroutine. Programming time and size can be shortened in tasks that have oft-repeated movements. The step and repeat instruction is even more powerful in palletizing operations. The programmer identifies the basic motions required, such as reaching and grasping or reaching and releasing, and then enters the direction and distance, the offset, to the next part on the pallet. The step and repeat instruction performs the basic movement and then continually increments the reach distance by the offset provided in the program to automatically pick up and then place the next part until the task is completed. Repeat and step and repeat instructions are generally entered via a video terminal attached to the controller. A controller console and pendant are shown in Figure 11–3. A few controllers use a detachable terminal or personal computer that is connected only during programming or editing. Since a terminal or pendant is used only during programming, a detachable terminal can be used with many controllers. The result is a less expensive controller. Detachable terminals generally include disk drives and the associated controllers do not, prohibiting the continuous disk access technique used in long CP programs described earlier. Upper-end intelligent controllers may contain some or all of these features, and, like most other aspects of controllers, the names given to these special features vary widely among controllers.

Limitations of Intelligent Controllers

Ironically, it is the intelligent controller's greatest advantage, ease of programming, that also produces its greatest disadvantages. Since the program must be developed by teaching the robot its movements, programming time is down time for the robot and surrounding equipment. Although the programming procedure is quickly mastered, the creation of a good program may take an experienced programmer half a day or more. Some complex tasks may require the entry of literally thousands of points. This disadvantage reappears each time changes in the process or product occur which necessitate modifications in the program. And although several robots may perform similar tasks, each must be individually programmed; the program cannot be developed at a remote location and quickly loaded into each robot. If several robots are used in a process, programming down time can become very expensive.

Because the intelligent controller develops a program by collecting positional information as the robot is led through the desired motions, its program cannot be readily analyzed, modeled, or optimized on a computer. Such unskilled tasks as part handling and palletizing are easily modeled and optimized on a general-purpose computer. Improvements produced by such analysis cannot be introduced into the programs of intelligent controllers.

Tasks involved in assembly operations, a huge potential market for robotics, require a controller that is much more aware of the workpiece than most intelligent controllers can be. The needed controller must be able to communicate with sophisticated vision and tactile sensor controllers and to then use the information provided by those sensors in performing the task. These requirements point to the need for a programming language that has a rich variety of arithmetic/logic, conditional, and I/O instructions. The few decision-making and I/O instructions available in the most advanced intelligent controllers fall short of these requirements.

The movement of computer-aided design and manufacturing techniques from the research lab to the factory requires sophisticated controllers that can participate in hierarchical control schemes both as a slave and as a master. The intelligent controller, by definition, is not powerful enough to participate in such a system. It should be noted, however, that in simple stand-alone applications these limitations may not outweigh the simplicity of programming and lower cost of an intelligent controller. A company can evaluate use of an intelligent robot without the expense of a full-time programmer or robotics engineer. Many small and medium-sized companies are "getting their feet wet" with an intelligent controller.

Finally, the walk-through and some lead-through programming techniques require the user to be within the robot's work envelope during programming. Since the robot is powered up during programming, a potentially hazardous situation exists each time a new task is programmed or an existing task is edited. Built-in safety compliance systems minimize the risk of an accident during programming but do not totally eliminate it.

Just as mechanical controllers have been replaced by electronic controllers, the intelligent controller will give way to the very intelligent controller. Since intelligent controllers are computer based, the increasing power of the microprocessor will increase the sophistication of the controller. Increased use of vision and touch and the development of CADAM systems will precipitate the need for smarter controllers on each robot. These controllers will be able to be programmed using the lead- or walk-through techniques or through the higher-level languages used on very intelligent controllers.

REVIEW QUESTIONS

1. List two advantages of the intelligent controller over the nonintelligent controller.
2. Explain the role of operating system software in an intelligent controller.
3. Describe an intelligent controller's three major modes of operation.
4. Explain how a program is created using the lead-through technique.
5. Compare walk- and lead-through programming techniques for painting and palletizing operations.
6. Discuss use of input and output commands by an intelligent controller in a manufacturing setting.
7. Describe the input and output commands that may be available in some controllers.
8. Discuss the advantages and disadvantages of the simple programming techniques used by intelligent controllers.

VERY INTELLIGENT CONTROLLERS

The intelligent controller, while more powerful than the nonintelligent controller, has some serious limitations in applications that require long sequences of complex motions or evaluation of information supplied by intelligent sensors. Like the intelligent controller, the very intelligent controller is computer based, but its operating system software does not hide the computer from the user. The languages used on very intelligent controllers are generally extensions of standard computer languages. This means, of course, that the programmer should have previous computer experience. The power gained by this general-purpose software allows the intelligent controller to participate in hierarchical control schemes. As in the other controller groups, there is a broad range of abilities among very intelligent controllers that extends from the high end of the intelligent machines to integrated CADAM systems.

The computer hardware used in a very intelligent controller is much like that used in an intelligent controller. Sixteen- and 32-bit processors are prevalent, and while Digital Equipment's PDP 11 has been most often used, the increased power and decreased cost of the 32-bit microprocessors have made them popular recently. A very intelligent controller has a large amount of RAM, 64K to 256K, and is disk based; Winchesters are not uncommon. These controllers tend to look very much like general-purpose mini- and microcomputers with some special

I/O capabilities. In addition to the I/O lines needed to collect feedback and send control signals to the robot, all have serial communication capabilities which allow them to communicate with other intelligent controllers. The greatest difference between the intelligent and very intelligent controller is the operating system software used to develop the robot's program.

The operating system software found in most very intelligent controllers enables them to be programmed using the lead-through or walk-through techniques found in an intelligent controller. This allows a user without computer experience to purchase the more sophisticated controller but be able to use it immediately and then gradually utilize the higher-level programming capability as experience is gained. Programming that involves physical use of the robot, like the lead- and walk-through methods, is referred to as on-line programming. The advantages of on-line programming generally outweigh the disadvantages when the robot must perform simple tasks that are not changed often. The disadvantages of on-line programming become overwhelming when short runs of the item used in the task are expected, when the task becomes too long, or when the task becomes too complex. The relatively simple task of palletizing may require the entry of more than one thousand points on an intelligent controller without a step and repeat function. Lead-through entry of such a program would be error prone and very time consuming. Programming a complex assembly task using either the lead- or walk-through techniques can be nearly impossible as the sequence of intricate movements required overwhelms the programmer.

Very intelligent controllers offer the ability to program the robot off line. Off-line programming makes little or no use of the robot during the production of a program. An off-line program is not produced by using the computer as a digital tape recorder to remember and replay the movements. Instead, it is produced much like a traditional computer program, by selecting needed instructions from an instruction set and arranging them in the correct sequence. When the program has been completed, it is downloaded or transferred into the controller via a serial communications link. Off-line programming offers several advantages over on-line programming. Because the robot is not used during programming, down time is significantly reduced. The existing program can be edited for an upcoming change off line while the robot continues to perform the present task. New programs for future tasks can be developed in advance to minimize task changeover time. Off-line programming also makes remote programming possible. Since the robot is not used during programming, the program can be produced at a location other than the robot's work site. A programmer can work in a programming facility and take advantage of high-level emulators, simulators, editors, vast storage capacities, and printers normally found in

a computer facility. Since a program developed off line is transferred to the controller via a serial communications link, many robots performing the same task can be loaded with the same program, eliminating programming duplication. Off-line programming makes it possible to develop a program thousands of miles from the controller, then send it to the controller over a phone line with the final editing being performed on the shop floor. A large company may have a single well-equipped, well-staffed programming center which develops programs for several manufacturing facilities.

Most very intelligent controllers support real-time control of the manipulator. Intelligent and nonintelligent controllers simply store the desired manipulator movements and play them back on command. The underlying assumption is that the part manipulated by these controllers will be in the right place, in the right alignment, at the right time. A real-time controller stores positional information but does not calculate the trajectory of the manipulator until it is needed during execution of the program. At the time it is calculated, the trajectory can be adjusted to allow for misalignment of the part or controller. Information about the part can be supplied to the controller by intelligent sensors. Off-line programming allows the design of a control algorithm and program which includes this information in the movement calculations.

Programming Languages

The advantages of the very intelligent controller are provided by the ability to develop programs in a high-level language. There are nearly as many high-level robot languages as there are brands of very intelligent controllers. Each company has generally produced or purchased a unique language for its line of controllers. Many robot programming languages are extensions of standard high-level computer programming languages. A language extension adds special instructions to the language's normal repertoire that ease manipulation of the arm, examination of inputs, or the setting of outputs. The language's math and logic functions are left intact to allow manipulation of information from intelligent sensors and other controllers in the program. The language's original structure and syntax are not greatly changed, so a technician or engineer familiar with the computer language can quickly learn the robot's language. Other robot languages combine features of several high-level computer languages into a new robot language. Most programming languages support real-time control of the manipulator. Intelligent controllers store the desired path of the manipulator and play it back upon request. The underlying supposition is that the part manipulated will be properly placed at the correct time. There is little or no ability to change the trajectory during execution. There are presently

no standards for robot programming languages nor has one language been so widely used that it has become a *de facto* standard. A program written in any one robot's language is generally not compatible with another manufacturer's controller on any level. Furthermore, most controllers support only a single language. The user is, then, married to the language that is available for the robot purchased. The wide variety of languages available and the lack of more than one language for a single controller is not dictated by limitations of the controller hardware. Indeed, several intelligent controllers sold with different languages use the same DEC LSI 11 processor. Any robot programming language could be written for and implemented on any very intelligent controller available. While there have been discussions in the professional associations and the research universities of the desirability of a standard language, the market has not matured enough to support a standard. Eventually a few languages will become widely used and become *de facto* standards. Some of these will be versions of today's languages while others will result from artificial intelligence research and still others from CADAM research. The languages currently available vary in sophistication and power but all allow the controller to be programmed off line. VAL, HELP, RAIL, AML, MCL, and RPL are but six of the many robot languages in use today. Each of these languages includes decision-making instructions, loop instructions, subroutines, variable naming, real and integer variables, and special instructions to set velocity of the manipulator and operate the gripper. Most of these are interpreted languages and offer the characteristic friendliness and editing advantages of interpreters. The characteristics and unique features of each of these languages will be described.

VAL.   Val was developed for Unimation's Unimate and Puma lines of robots. It is a loose extension of BASIC which runs on DEC's LSI 11 processor. VAL supports on-line walk-through programming as well as off-line high-level programming and a combination of both in which coordinate data is collected on line and the program that manipulates the robot through those positions is written off line. VAL includes the ability to communicate with intelligent vision and tactile sensors. A simple pick-and-place program is shown below.

```
.PROGRAM PICK
    1. MOVE P10
    2. MOVE P11
    3. SPEED 30
    4. MOVES P20
    5. CLOSEI 0.00
```

6. MOVE P20
7. MOVE P11
8. SPEED 30
9. MOVE P10
10. OPENI 0.00
.END

The instructions are numbered in order of performance. MOVE is one of the most frequently used commands. MOVE specifies a straight-line move to the point specified. The coordinates or points are labeled PXX in this program. The coordinates appear as a file that is read by the program. The coordinate file may be built by identifying the desired points on line by moving the manipulator or may be generated by a geometric model algorithm supplied by the user.

HELP. HELP was developed for use with General Electric's Allegro assembly robots. It is a loose extension of Pascal which runs on DEC's LSI 11 processor. HELP includes the ability to supervise more than one arm with a single controller. It does not include geometric models but operates totally in a joint coordinate system. HELP includes the ability to communicate with an intelligent tactile sensor but not with an intelligent vision sensor.

AML. AML (*a manipulator language*) was developed for use on IBM's RS/1 assembly robot. It is a new, highly structured language that draws on LISP, ALGOL, and APL and runs on IBM's Series/I processor. A subset is available which runs on IBM's PC processor and requires somewhat less computer programming experience. AML is an interactive language that is both textual and menu based. Its structure is quite regular and exception type fixes to problems are discouraged. It has recently been used with both intelligent tactile and vision sensors.

MCL. MCL (*manufacturing control language*) was developed by McDonnell Douglas under contract with the USAF for the ICAM project. It has been implemented on Cincinnati Milacron's T3 robot. MCL is an extension of APT, the widely used numerical control programming language. It was developed to run on an IBM 370 mainframe computer, although a DEC PDP 11 version has been developed. MCL allows development of programs which will control not only the robot but also the surrounding equipment in a work cell. Instructions are included that allow MCL to utilize data from intelligent tactile and vision sensors.

RPL.   RPL (*robot programming language*) was developed by SRI to aid in the configuration of automated manufacturing systems. RPL draws on Pascal, FORTRAN, and LISP and runs on DEC's LSI 11 processor. An unusual feature of the language is that its most often executed command is the subroutine call. A program consists of a series of subroutines that are called, or executed, sequentially. RPL allows communication with intelligent vision sensors.

RAIL.   RAIL was developed by Automatix for use with robots and vision systems. RAIL is an extension of Pascal that runs on an MC68000 processor in Automatix's AI32 controller. It supports either on-line walk-through programming or off-line high-level programming. In the walk-through mode, operating system software produces a RAIL program as the robot is led through the desired motions. A simple pick-and-place RAIL program is shown below.

```
        BEGIN
    ;Pick up part.
        OPEN
        APPROACH 2.0 FROM LINE1
        MOVE LINE1 WITH SPEEDSCHED(2)
        CLOSE
        DEPART 2.0
    ;Place part.
        APPROACH 2.0 FROM PRESS
        MOVE GLUE WITH SPEEDSCHED(2)
        OPEN
        DEPART 2.0
        END
```

These six languages, from the relatively simple VAL to the structured RAIL to the new and powerful AML, are representative of all currently available robot languages. Which language is best? Each is probably best in particular settings. The complexity of the task, the amount of intelligent I/O information that must be used by the controller, and the programming experience of the user must all be considered when choosing the "best" language for a given task. Increased sophistication and power in a language generally require increased experience and sophistication in the programmer. The converse is also true. VAL is certainly simpler to use than AML but is less powerful than AML. Keep in mind that presently a programmer cannot choose a language for a given robot, since its controller can only execute its manufacturer's language.

A hierarchical control system involves one computer supervising the actions of other computers in an organizational scheme which resembles the chain of command in any organization. A hierarchical control scheme is shown in Figure 12–1. Notice that at each level the computer has only a single controller above it but may have one or more computers below it. The computers at the bottom of the figure are very intelligent robot controllers. They are responsible for the control of a specified machine or robot. The computers at the next level up are work cell supervisors. A supervisor directs the actions of more than one very intelligent controller. The supervisor coordinates the interactions between those controllers beneath it. A supervisor might, for example, be responsible for all action within a single work cell, which could include several machines each of which is controlled by its own very intelligent controller. The next-higher-level controller, the shop supervisor, coordinates work cell supervisors to ensure maximum rate of materials flow through the process. It foresees backups or delays and manipulates the materials handling system and work cell supervisors to avoid them. Work cell and shop supervisor hardware includes 32-bit micro- or miniprocessors, sophisticated serial and local network communications interfaces, a very
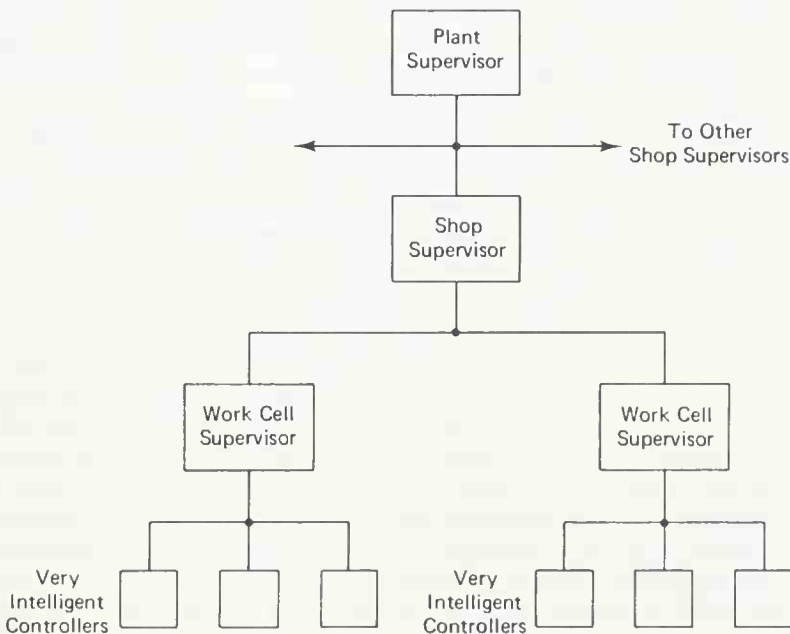
Figure 12–1.   Hierarchical control system.

large amount of RAM, high-density disk drives, and printers. The computer at the top of the system is the plant supervisor. The plant supervisor is responsible for the entire operation within the facility. Plant supervisor hardware includes a mainframe processor, a very large amount of virtual RAM, multiple hard disk drives, communications interfaces, and printers.

In such a control system commands flow downward from the plant supervisor to the shop supervisors, from the shop supervisors to the work cell supervisors, and from the work cell supervisors to the individual machine controllers. Information about the status of the operation flows upward from the controllers on the lower levels to their supervisors on levels above. Decisions that affect each component of the process are software based and are made by the controller responsible for the resulting actions within constraints provided by its supervisor. At each higher level of control the constraints become less task oriented and more process oriented. The plant supervisor software does not consider the specific movements of any single robot or machine but instead considers the ordering and delivery of raw materials to meet the production schedules. Conversely, the very intelligent controller at the bottom of the hierarchy does not consider ordering and delivery of raw materials but instead considers the actual and desired position of the manipulator it is responsible for. The view at the top is quite broad while the view at the bottom is necessarily narrow.

Hierarchical control depends on the ability of each controller to communicate with those above it and below it. The communications interfaces must be both hardware and software compatible. Hardware compatibility does not require identical processors or control systems at each level; it requires electrical signal level and timing compatibility. RS 232, the serial communications standard, is often used between controllers, and recently some systems have employed local area network hardware. Software compatibility is much more difficult to achieve. The software must be compatible in the data types and data structure used and in the command format used. Underlying all specific control, software must be an operating system that supports the communication necessary in a hierarchical system. Some CADAM systems are examples of hierarchical systems in which the database formed in the design process is passed to the controllers supervising the manufacturing equipment. Because it is programmable in a high-level language, the very intelligent controller is usable in hierarchical systems. Hierarchical control systems are just beginning to be implemented at the manufacturing plant level, but many intelligent and very intelligent controllers use a simple hierarchical scheme. These controllers place a single-chip 8-bit microprocessor-based controller at each joint to make feedback adjustments in the servo system for that joint. The program for using the

feedback is stored in ROM; it is system software and is not generated by the user. The main controller is then free to calculate the trajectory and consider information from intelligent sensors. The joint processors are totally invisible to the user and totally subservient to the intelligent and very intelligent controller.

Vision Systems

Very intelligent controllers have the ability to make real-time adjustments in a program's positional data to compensate for variables in the workpiece. This ability is sometimes referred to as adaptive control. To make these adjustments the controller needs more sophisticated information about the current state of the process than can be provided by the simple go–no go limit switches and sensors generally used with nonintelligent controllers. A vision system can provide the robot controller with information about the location, orientation, and type of part that is to be handled. Machine vision systems are used for recognition and verification of parts, for inspection and sorting of parts, for noncontact measurements, and for providing part position and orientation information to the robot controller.

The components of a typical machine vision system are shown in Figure 12–2. The scene is viewed by a video camera which converts it into a series of electrical signals. The camera may be mounted in a stationary position above the work place to view the workpieces as they become available to the robot or it may be mounted on the manipulator arm to view the scene as the arm is moved. The small size and weight and the ruggedness of solid-state cameras have made them popular with vision system designers. The fineness of detail in a frame of information produced by a camera is its resolution. The higher the resolution, the greater the amount of detail shown or the smaller the characteristic that can be discerned. A frame is composed of tiny blocks placed side by
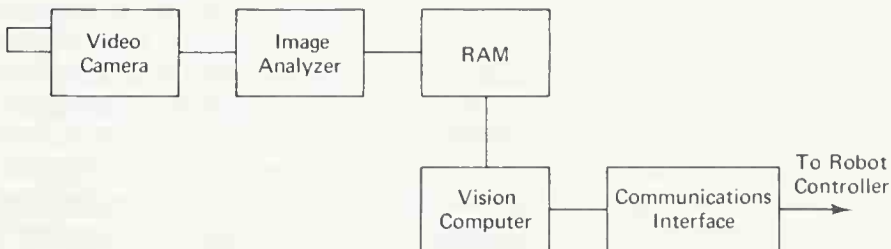
Figure 12–2.   Machine vision system.

side on the screen. These blocks are called picture elements or pixels. Resolution is expressed as the number of pixels that are produced by the camera for any scene in a $V \times H$ specification. Cameras produce pictures with resolutions that vary from as low as 128×128 pixels to as high as 320×480 pixels. The resolution needed by a camera is determined by the amount of detail which must be seen by the system.

The electrical signals generated by the camera are passed to the image analyzer. The image analyzer converts the analog video signal into a matrix of numbers which can be manipulated by the computer. Machine vision may have binary, gray scale, or color characteristics. Binary and gray scale vision produce black and white images while color includes hue information. Binary vision is most commonly used because it produces enough information to satisfy the requirements of the robot controller in many applications and because it is simpler and less expensive to implement. A gray scale image includes shades of gray that range from near black to near white. A binary image is composed only of black and white pixels which are represented as zeros and ones. The surface of the object viewed by a binary system contrasts with the surface of the table supporting the object, and a black and white silhouette of the object is produced in which the edges and holes of the object are plainly discernable. The amount of contrast required by the system to produce an image is called the threshold. The sensitivity of the threshold must be adjusted to produce an image of the object each time the object is viewed without producing spurious images due to ambient light "noise." Special lighting of the viewing area is used to produce high contrast and reduce the effects of ambient light. High-intensity lights, strobe lights, colored lights, and camera filters are used to produce the contrast needed. Although back lighting produces excellent contrast, it may not be used due to dust accumulation in or mechanical constraints of the work cell. Front lighting is most often used and is always used when top surface features of the object must be viewed.

The digitized, binary image is stored in RAM and made available to the computer. The computer analyzes the image to define the objects viewed, extracts desired features from the objects, and classifies the objects according to specifications supplied by the user. Object definition is often performed using connectivity theory. Connectivity forms objects by grouping adjacent darkened pixels together to form a blob. The blobs formed in a frame are then subjected to feature extraction and classification. Feature extraction algorithms perform measurements on each blob to build a table of characteristics which can be used in classification. Perimeter, total area, maximum height and width, number, position and radii of holes, elongation and compaction indices, width of a rectangle placed around the image by the computer (called a bounding rectangle), and the orientation of the blob in the scene are features typically ex-

tracted from the image and stored for each blob. Classification algorithms then compare the characteristics of each blob with learned characteristics of the objects to be recognized to discriminate between blobs in an image. If the blob's features match those of a learned part, the system labels the blob as that part. The level of correspondence between the blob's characteristics and those of a learned part are user selectable. The software that performs this analysis is sometimes referred to as the nearest-neighbor algorithm. Vision systems allow the user to specify which features are extracted and used during classification. The larger the number of features extracted and used, the greater the processor time required to classify the blobs. The types of shapes, together with their areas and unique characteristics, determine the number of features needed for classification of blobs. Recognition time may vary from 0.01 to 1 sec depending on the complexity of the scene and the number of characteristics used in classification. Because the definition, feature extraction, and classification programs are complex and require a lot of processor time, the computer shown in Figure 12–2 is a stand-alone unit; it is not the very intelligent controller used by the robot. The Digital Equipment LSI 11 and Motorola 68000 processors have been widely used. The vision computer communicates with the robot's very intelligent controller via the serial communications interface shown in Figure 12–2.

There are no standards for vision software. All systems are taught the parts to be recognized by repeated exposure to the parts in a learn mode. During the learn mode, operating system software performs feature extraction on the part and a standard table of characteristics is stored in memory. This table is used during classification. Some vision systems are menu driven, in which the user is asked to choose which parameters will be extracted and used for classification. Menu-driven systems are relatively easy to use and require little programming experience. Operating system software includes all software needed; the user only chooses parameters. Other vision systems allow the user access to the recognition software and to develop custom recognition programs. Custom programs are more efficient than the general-purpose algorithms found in a menu-driven system and, therefore, run faster.

Most intelligent robot controller languages include or are being revised to include vision commands that allow the controller to communicate with the vision computer. VAL includes the vision instructions PICTURE and LOCATE. A PICTURE command, when issued to the vision system, causes the scene to be scanned, digitized, analyzed, and classified. The LOCATE command directs the vision computer to determine the location of a named part and to return its coordinates and orientation. These commands are fairly typical of those found in the other languages. There are no standards, however, for the form of an

instruction or format of the data returned or communications protocol between the robot controller and the vision computer. Again the system designer is limited to what's available for the robot being used.

Machine vision allows applications of robots in complex assembly operations. Vision systems are relatively new, however, and relatively expensive. It may be more cost-effective to design special part presentation or handling fixtures than to use a vision system. If the application requires gray scale or color sensing, special fixturing is probably cheaper. As the vision field matures and the cost of 32-bit microprocessors decreases, the cost of gray scale and color vision will fall. As *de facto* hardware and software standards develop, vision will be more widely used.

Because it can work within a very intelligent manufacturing system, the very intelligent controller will eventually replace all less intelligent controllers. Even those robots which perform simple tasks will be supervised by a very intelligent controller. The ability to communicate with other processors will be needed in the automated factory of the future.

REVIEW QUESTIONS

1. Discuss two advantages of the very intelligent controller over the intelligent controller.
2. Explain the difference between on- and off-line programming.
3. List four programming languages.
4. Why are there no standard robot languages?
5. Sketch and explain a hierarchical control system that includes a robot.
6. Discuss the distribution of decision making in a hierarchical control system.
7. Define the terms *resolution, pixel, binary vision, gray scale vision, blob,* and *feature extraction.*
8. Describe the process used to classify objects in a vision system.

Appendix

ELECTRICAL/ELECTRONIC SYMBOLS AND FLUID POWER SYMBOLS

FIXED RESISTOR

TAPPED RESISTOR

VARIABLE RESISTOR

RHEOSTAT

THERMISTOR

FIXED CAPACITOR

VARIABLE CAPACITOR

POLARIZED CAPACITOR

TURNSTILE ANTENNA

DIPOLE ANTENNA

LOOP ANTENNA

BATTERY

GENERAL ALTERNATING-CURRENT SOURCE

PERMANENT MAGNET

PIEZOELECTRIC CRYSTAL

THERMOCOUPLE

THERMAL CUTOUT

WIRES CROSSING; NOT CONNECTED

WIRES CONNECTED

SHIELDED CONDUCTOR

SHIELDED 2-CONDUCTOR CABLE

GROUPING OF LEADS

CIRCUIT RETURN

GROUND   CHASSIS   COMMON

CONTACTS (NORMALLY CLOSED)

CONTACTS (NORMALLY OPEN)

CONTACTS (TRANSFER)

SWITCH (SINGLE-POLE, SINGLE-THROW)

SWITCH (SINGLE-POLE, DOUBLE-THROW)

SWITCH (DOUBLE-POLE, SINGLE-THROW)

SWITCH (DOUBLE-POLE, DOUBLE-THROW)

MULTIPOSITION SELECTOR SWITCH (ANY NUMBER OF POSITIONS MAY BE SHOWN)

PUSH-BUTTON SWITCH (NORMALLY OPEN)

PUSH-BUTTON SWITCH (NORMALLY CLOSED)

PUSH-BUTTON SWITCH (2-CIRCUIT)

LIMIT SWITCH (SPRING RETURN, NORMALLY OPEN)

LIMIT SWITCH (SPRING RETURN, NORMALLY OPEN, HELD CLOSED)

LIMIT SWITCH (SPRING RETURN, NORMALLY CLOSED)

LIMIT SWITCH (SPRING RETURN, NORMALLY CLOSED, HELD OPEN)

OPEN SWITCH, TIME-DELAY CLOSING   TDC

CLOSED SWITCH, TIME-DELAY OPENING   TDO

OPEN SWITCH, TIME-DELAY OPENING   TDO

CLOSED SWITCH, TIME-DELAY CLOSING   TDC

FLOW SWITCH (CLOSES ON FLOW INCREASE)

FLOW SWITCH (OPENS ON FLOW INCREASE)

LIQUID-LEVEL SWITCH (CLOSES ON RISING LEVEL)

LIQUID-LEVEL SWITCH (OPENS ON RISING LEVEL)

PRESSURE-ACTUATED SWITCH (CLOSES ON RISING PRESSURE)

PRESSURE-ACTUATED SWITCH (OPENS ON RISING PRESSURE)

TEMPERATURE-ACTUATED SWITCH (CLOSES ON RISING TEMPERATURE)

TEMPERATURE-ACTUATED SWITCH (OPENS ON RISING TEMPERATURE)

FUSE

CIRCUIT BREAKER (SINGLE POLE)

CIRCUIT BREAKER (THREE POLE)

COIL (AIR CORE)

COIL (MAGNETIC CORE)

COIL (TAPPED)

COIL (ADJUSTABLE)

TRANSFORMER (AIR CORE)

TRANSFORMER (MAGNETIC CORE)

AUTOTRANSFORMER

CURRENT TRANSFORMER

RELAY,
TRANSFER CONTACTS

OR   OR ®
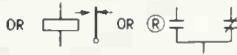
CIRCUIT TERMINAL

TERMINAL BOARD
OR STRIP   OR
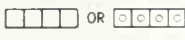
FEMALE CONNECTOR

MALE CONNECTOR

ENGAGED CONNECTORS

ENGAGED COAXIAL CONNECTORS
(OUTSIDE CONDUCTOR CARRIED THROUGH)
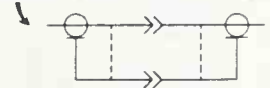
JACK
(2-CONDUCTOR)

PLUG
(2-CONDUCTOR)

POWER SUPPLY CONNECTORS
NONPOLARIZED,
2-CONDUCTOR MALE

OR   OR

POLARIZED,
3-CONDUCTOR FEMALE

OR   OR

ELECTRON-TUBE SYMBOLS

VACUUM-TYPE ENVELOPE

GAS-FILLED ENVELOPE

FILAMENT AND DIRECTLY
HEATED CATHODE

INDIRECTLY
HEATED CATHODE

COLD
CATHODE

PHOTOCATHODE

POOL
CATHODE

IONICALLY
HEATED CATHODE

GRID

DEFLECTING
ELECTRODE

ANODE
OR PLATE

TARGET OR
X-RAY ANODE

DYNODE

IGNITOR
OR STARTER

VACUUM-TYPE
DIODE   OR
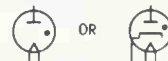
GAS-FILLED
DIODE   OR

COLD-CATHODE,
GAS-FILLED DIODE

VACUUM-TYPE
PHOTOTUBE

MULTIPLIER-TYPE
PHOTOTUBE

X-RAY TUBE

VACUUM-TYPE
TRIODE   OR
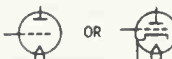
GAS-FILLED
TRIODE
(THYRATRON)   OR
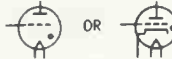
VACUUM-TYPE
TETRODE

VACUUM-TYPE
PENTODE

BEAM-
POWER TUBE

MERCURY-POOL
TUBE (IGNITRON)

CATHODE-RAY TUBE
(ELECTROSTATIC DEFLECTION)
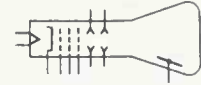
CATHODE-RAY TUBE
(ELECTROMAGNETIC DEFLECTION)
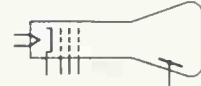
SEMICONDUCTOR SYMBOLS

DIODE   (A) ANODE   CATHODE (K)

CAPACITIVE DIODE
(VARACTOR)   OR

TEMPERATURE-
DEPENDENT DIODE

PHOTOSENSITIVE
DIODE

PHOTOEMISSIVE
DIODE

ZENER
DIODE   OR

THYRECTOR
DIODE   OR

TUNNEL
DIODE   OR

TRIGGER DIAC, UNIDIRECTIONAL
K A   OR   A K
NPN   PNP
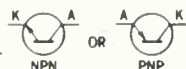
TRIGGER DIAC, BIDIRECTIONAL
T T   OR   T T
NPN   PNP
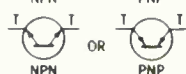
THYRISTOR, REVERSE-BLOCKING-DIODE TYPE
A K   OR   A K
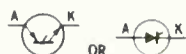
THYRISTOR, REVERSE-BLOCKING-TRIODE TYPE (SOLID-STATE THYRATRON, OR SCR)
A G K

THYRISTOR, BIDIRECTIONAL-DIODE TYPE
T T

THYRISTOR, BIDIRECTIONAL-TRIODE TYPE
T G T

BIPOLAR TRANSISTOR
E C PNP B
E C NPN B
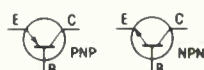
PHOTOTRANSISTOR
E C PNP B
E C NPN B
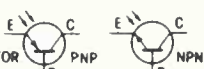
DARLINGTON TRANSISTOR
B C NPN E
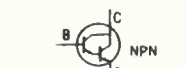
UNIJUNCTION TRANSISTOR
E B₂ B₁ N-TYPE BASE
E B₂ B₁ P-TYPE BASE
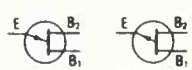
N-CHANNEL JFET
G D S OR G D S
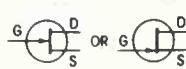
P-CHANNEL JFET
G D S OR G D S
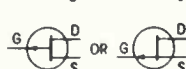
N-CHANNEL MOSFET, DEPLETION TYPE
G D U S

N-CHANNEL MOSFET, ENHANCEMENT TYPE
G D U S

P-CHANNEL MOSFET, DEPLETION TYPE
G D U S

P-CHANNEL MOSFET, ENHANCEMENT TYPE
G D U S

PHOTOVOLTAIC TRANSDUCER (SOLAR CELL)

PHOTON-COUPLED ISOLATOR (PHOTOEMISSIVE DIODE & PHOTOTRANSISTOR)
A C K B E
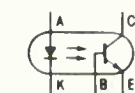
ELECTRICAL BELL; TELEPHONE RINGER   OR
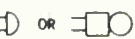
LOUDSPEAKER

MICROPHONE   OR

HANDSET

LAMP (GENERAL)
* REPLACE WITH LETTER(S) DESIGNATING TYPE

INCANDESCENT LAMP (ILLUMINATING)

INCANDESCENT LAMP (INDICATING)

FLUORESCENT LAMP

NEON GLOW LAMP (AC)

NEON GLOW LAMP (DC)

BALLAST LAMP

METER
* REPLACE WITH LETTER(S) DESIGNATING TYPE.

GENERATOR (GENERAL)   G   OR   GEN
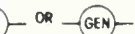
DC GENERATOR   G

AC GENERATOR   G

SYNCHRONOUS GENERATOR   GS

MOTOR (GENERAL)   M   OR   MOT
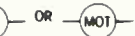
DC MOTOR   M

AC MOTOR   M

SYNCHRONOUS MOTOR   MS

GENERATOR OR MOTOR FIELD (SERIES)

GENERATOR OR MOTOR FIELD (SHUNT)

SYNCHRO (GENERAL)

ANALOG AND DIGITAL LOGIC SYMBOLS:

OPERATIONAL AMPLIFIER   OR
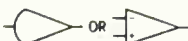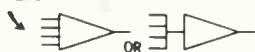
SUMMING AMPLIFIER   OR
(4 INPUTS & 1 OUTPUT SHOWN)

ELECTRONIC MULTIPLIER

ELECTRONIC DIVIDER

ELECTRONIC FUNCTION GENERATOR

GENERALIZED INTEGRATOR

AND FUNCTION

OR FUNCTION

NAND FUNCTION

NOR FUNCTION

EXCLUSIVE OR FUNCTION

INVERTER (NOT) FUNCTION

FLIP-FLOP (GENERAL)   FF
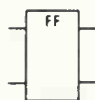
FLUID POWER SYMBOLS

FLUID CONDUCTORS

WORKING LINE
(MAIN)

PILOT LINE
(FOR CONTROL)

EXHAUST AND
LIQUID DRAIN LINE

FLOW DIRECTION
HYDRAULIC

FLOW DIRECTION
PNEUMATIC

LINE WITH
FIXED RESTRICTION
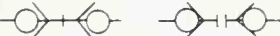
FLEXIBLE
LINE

QUICK DISCONNECT
WITHOUT CHECKS

CONNECTED   DISCONNECTED

QUICK DISCONNECT
WITH ONE CHECK

CONNECTED   DISCONNECTED

QUICK DISCONNECT
WITH TWO CHECKS

CONNECTED   DISCONNECTED

ENERGY AND FLUID STORAGE

VENTED
RESERVOIR

PRESSURIZED
RESERVOIR

RESERVOIR WITH
CONNECTING LINES

ABOVE FLUID LEVEL

BELOW FLUID LEVEL

SPRING-LOADED
ACCUMULATOR

GAS-CHARGED
ACCUMULATOR

WEIGHTED
ACCUMULATOR

RECEIVER FOR AIR
OR OTHER GASES

FLUID CONDITIONERS

HEATER

INSIDE TRIANGLES INDICATE
THE INTRODUCTION OF HEAT

HEATER

OUTSIDE TRIANGLES INDICATE
A LIQUID HEATING MEDIUM

HEATER

OUTSIDE TRIANGLES INDICATE
A GASEOUS HEATING MEDIUM

COOLER   OR

INSIDE TRIANGLES INDICATE
HEAT DISSIPATION

COOLER   OR

OUTSIDE TRIANGLES INDICATE
A LIQUID OR GASEOUS COOLING MEDIUM

TEMPERATURE
CONTROLLER   OR

OUTSIDE TRIANGLES INDICATE A
LIQUID OR GASEOUS MEDIUM

FILTER
OR STRAINER

SEPARATOR
WITH MANUAL DRAIN

SEPARATOR
WITH AUTOMATIC DRAIN

FILTER–SEPARATOR
WITH MANUAL DRAIN

FILTER–SEPARATOR
WITH AUTOMATIC DRAIN

DESSICATOR
(CHEMICAL DRYER)

LUBRICATOR
WITHOUT DRAIN

LUBRICATOR
WITH MANUAL DRAIN

LINEAR DEVICES

SINGLE-ACTING CYLINDERS
(HYDRAULIC AND PNEUMATIC)

DOUBLE-ACTING CYLINDER
WITH SINGLE END ROD

DOUBLE-ACTING CYLINDER
WITH DOUBLE END ROD

PRESSURE
INTENSIFIER

HYDRAULIC   PNEUMATIC

SERVO POSITIONER

ACTUATORS AND CONTROLS

SPRING
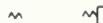
MANUAL

PUSH BUTTON

LEVER

PEDAL OR TREADLE

MECHANICAL

DETENT

SHORT LINE INDICATES
DETENT IN USE

PRESSURE
COMPENSATED

SOLENOID
(SINGLE WINDING)
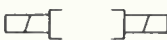
REVERSING
MOTOR

PILOT PRESSURE
(REMOTE SUPPLY)

PILOT PRESSURE
(INTERNAL SUPPLY)

ACTUATION BY
RELEASED PRESSURE
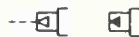
BY REMOTE   BY INTERNAL
EXHAUST   RETURN

PILOT CONTROLLED,
SPRING CENTERED

PILOT
DIFFERENTIAL

SOLENOID
OR PILOT

EXTERNAL   INTERNAL
PILOT SUPPLY   PILOT SUPPLY
                 AND EXHAUST

SOLENOID
AND PILOT

ACTUATION BY
THERMAL CHANGE

LOCAL   WITH BULB FOR
SENSING   REMOTE SENSING

SERVO

ROTARY DEVICES

UNIDIRECTIONAL   BIDIRECTIONAL
HYDRAULIC PUMP, FIXED DISPLACEMENT

UNIDIRECTIONAL   BIDIRECTIONAL
HYDRAULIC PUMP, VARIABLE DISPLACEMENT,
NONCOMPENSATED

UNIDIRECTIONAL   BIDIRECTIONAL
HYDRAULIC PUMP, VARIABLE DISPLACEMENT,
PRESSURE COMPENSATED

UNIDIRECTIONAL   BIDIRECTIONAL
HYDRAULIC MOTOR, FIXED DISPLACEMENT

UNIDIRECTIONAL   BIDIRECTIONAL
HYDRAULIC MOTOR, VARIABLE DISPLACEMENT

OPERATES AS PUMP
IN ONE DIRECTION,
AS MOTOR IN OTHER DIRECTION
HYDRAULIC PUMP–MOTOR

OPERATES IN ONE DIRECTION
AS EITHER PUMP OR MOTOR
HYDRAULIC PUMP–MOTOR

OPERATES IN BOTH DIRECTIONS
AS EITHER PUMP OR MOTOR
HYDRAULIC PUMP–MOTOR, VARIABLE DISPLACEMENT,
PRESSURE COMPENSATED

PNEUMATIC PUMP,   COMPRESSOR
FIXED DISPLACEMENT

PNEUMATIC PUMP,   VACUUM PUMP
FIXED DISPLACEMENT

PNEUMATIC
MOTOR
                 UNIDIRECTIONAL   BIDIRECTIONAL

OSCILLATOR
                 HYDRAULIC   PNEUMATIC

ELECTRIC
MOTOR

INTERNAL
COMBUSTION
ENGINE

INSTRUMENTS AND ACCESSORIES

PRESSURE
INDICATING AND
RECORDING

TEMPERATURE
INDICATING AND
RECORDING

FLOW-RATE
METER

TOTALIZING
METER

VENTURI

ORIFICE
PLATE

PITOT
TUBE

NOZZLE
                 HYDRAULIC   PNEUMATIC

PRESSURE SWITCH

MUFFLER

VALVES, BASIC SYMBOLS

ENVELOPES

ENVELOPES WITH PORTS
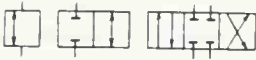
PORTS INTERNALLY BLOCKED
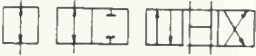
FLOW PATHS INTERNALLY OPEN

TWO-WAY VALVES (2-PORTED)

SIMPLIFIED   OFF   ON
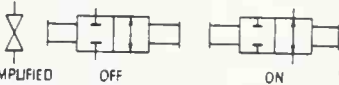
MANUAL SHUTOFF ON-OFF VALVE

SIMPLIFIED

CHECK VALVE

COMPOSITE
(FLOW BLOCKED TO RIGHT;
PERMITTED TO LEFT.)
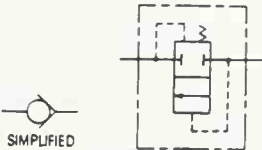
CHECK VALVE,
PILOT-OPERATED TO OPEN
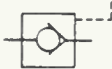
CHECK VALVE,
PILOT-OPERATED TO CLOSE

TWO-
POSITION TWO-
WAY VALVES

NORMALLY   NORMALLY
CLOSED   OPEN

NORMALLY   NORMALLY
CLOSED   OPEN
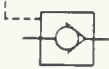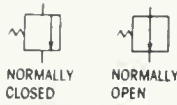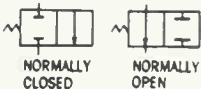
INFINITE-POSITION TWO-WAY VALVES

THREE-WAY VALVES

NORMALLY OPEN   NORMALLY CLOSED

TWO-POSITION

PRESSURE IS DISTRIBUTED
FIRST TO ONE PORT, THEN
THE OTHER
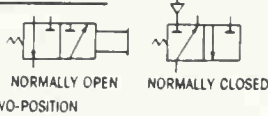
TWO-POSITION DISTRIBUTOR

TWO-POSITION,
TWO-PRESSURE

DOUBLE CHECK VALVE
WITHOUT CROSS BLEED
(ONE-WAY FLOW)
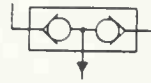
DOUBLE CHECK VALVE
WITH CROSS BLEED
(REVERSE FLOW PERMITTED)

FOUR-WAY VALVES

NORMAL

ACTUATED

TWO-POSITION

NORMAL

ACTUATED LEFT

ACTUATED RIGHT
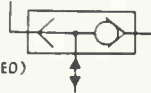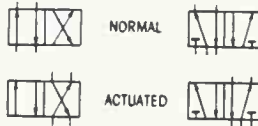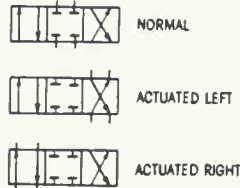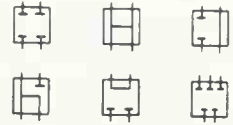
THREE-POSITION

TYPICAL FLOW PATHS FOR CENTER CONDITION
OF THREE-POSITION, FOUR-WAY VALVES

TRANSITION
SYMBOL

TWO-POSITION, SNAP ACTION WITH TRANSITION

INFINITE POSITIONING
(BETWEEN OPEN AND CLOSED)

NORMALLY
CLOSED

NORMALLY
OPEN
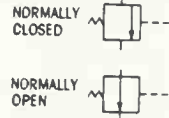
PRESSURE CONTROL VALVES

PRESSURE
RELIEF

NORMAL   ACTUATED
           (RELIEVING)
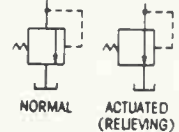
SEQUENCE
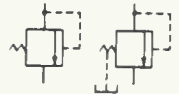
PRESSURE
REDUCING

PRESSURE
REDUCING
AND RELIEVING

AIR LINE PRESSURE
REGULATOR (ADJUSTABLE, RELIEVING)

INFINITE POSITIONING VALVES:
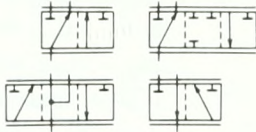
THREE-WAY VALVES
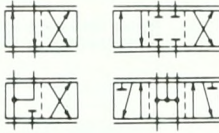
FOUR-WAY VALVES

FLOW-CONTROL VALVES:

ADJUSTABLE, NONCOMPENSATED
(FLOW CONTROL IN EACH DIRECTION)

ADJUSTABLE,
WITH BYPASS
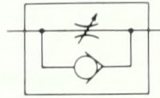
FLOW CONTROLLED TO RIGHT,
FLOW TO LEFT BYPASSES CONTROL.

ADJUSTABLE AND PRESSURE
COMPENSATED, WITH BYPASS
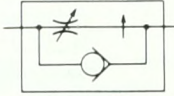
ADJUSTABLE, TEMPERATURE
AND PRESSURE COMPENSATED
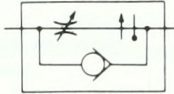
AIR LINE ACCESSORIES:
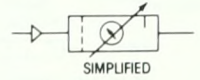
SIMPLIFIED
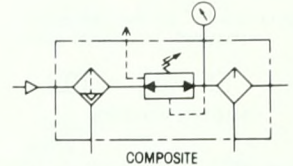
COMPOSITE

FILTER, REGULATOR, AND LUBRICATOR

INDEX